
COAL IN A NEW CARBON AGE

Powering a Wave of Innovation in
Advanced Products & Manufacturing





May 23, 2019

The Honorable Rick Perry
U.S. Secretary of Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585

Dear Mr. Secretary:

On behalf of the members of the National Coal Council (NCC), pursuant to your letter dated August 31st, 2018, we are pleased to submit to you, the report “Coal in a New Carbon Age: Powering a Wave of Innovation in Advanced Products & Manufacturing.” The report’s primary focus is on assessing opportunities to enhance the use of U.S. coal beyond conventional markets for power generation and steelmaking. The report details and prioritizes market-scale opportunities for coal-to-products, including coal-to-liquids, coal to solid carbon products, rare earth elements and coal beneficiation, as well as life science, bio-tech, medical and agricultural applications.

The opportunity for the U.S. represented by these markets is compelling. Advancing new markets for coal can enhance U.S. national defense security, bolster the nation’s energy and mineral security, enhance our nation’s environment objectives and contribute to America’s economic prosperity. It can also provide a needed socio/economic boost by creating new alternative higher tech demand for the nation’s coal production as well as provide the prospect of a carbon manufacturing “renaissance” in some of the nation’s economically depressed coal States and communities hit by the past decades’ decline in coal production and use.

The NCC conducted a nine-block analysis to provide a qualitative, directional assessment of market opportunities based on market attractiveness and competitive strength. This analysis indicates that the most significant growth opportunities for U.S. coal are in producing high-value specialty materials and products at reduced costs. That cost reduction is in part a direct result of the cost competitive pricing of coal over other carbon feedstocks like petroleum. Pursuit of these markets could constitute a step-change for U.S. coal. Coal could become a new, innovative, low-cost solution to creating advanced materials and products across many important sectors, including aerospace, automotive, construction, electronics, low-carbon energy like wind and solar, agriculture, and environmental, medical and life sciences.

The NCC recommend three primary strategic objectives be pursued by the U.S. Department of Energy to accelerate U.S. manufacturing of coal-derived solid carbon products, chemicals, fuels and rare earth elements.

- **Establish a focused R&D program on coal-to-products.**
Additional research and development (R&D) is needed to achieve commercially viable technical performance-to-cost ratios for the manufacture of coal-derived solid carbon products, chemicals, fuels, and REEs in the U.S.

- **Accelerate research-to-commercial deployment in coal-to-products markets.** Competing successfully in a global economy requires that the U.S. bring new technologies and related manufacturing to market much faster via replicable modular systems. To avoid being out-paced by other countries, gaps in funding and delays in progression from research to commercial deployment, including new-skills workforce development must be eliminated.
- **Incentivize private sector investment in coal-to-products production and manufacturing sectors.**
Efficient use of public and private sector financial capital requires alignment of private sector interests and investment readiness with government public sector R&D and economic development investment plans, as well as with defense procurement schedules. Steps must be taken to establish a stronger private sector investment appetite for first-of-a-kind (FOAK) and subsequent single-digit coal conversion plants and end-product factories, in order to quickly move DOE supported coal-to-products technologies into commercial operation, to create jobs and to improve U.S. balance of trade.

Specific actionable tactics recommended to achieve these strategic objectives are detailed in Chapter 3 of the report. Tactical recommendations are framed to specify both what must be done and why.

The nation's abundant coal resources are well-suited to securely support the U.S. as it enters the New Carbon Age, powered by innovation in both advanced products and advanced manufacturing.

Thank you for the opportunity to prepare this report. The Council stands ready to address any questions you may have regarding its findings and recommendations.

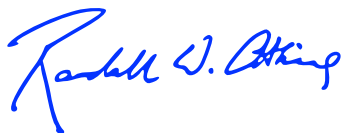
Sincerely,



Danny Gray
National Coal Council Chair 2019-2020



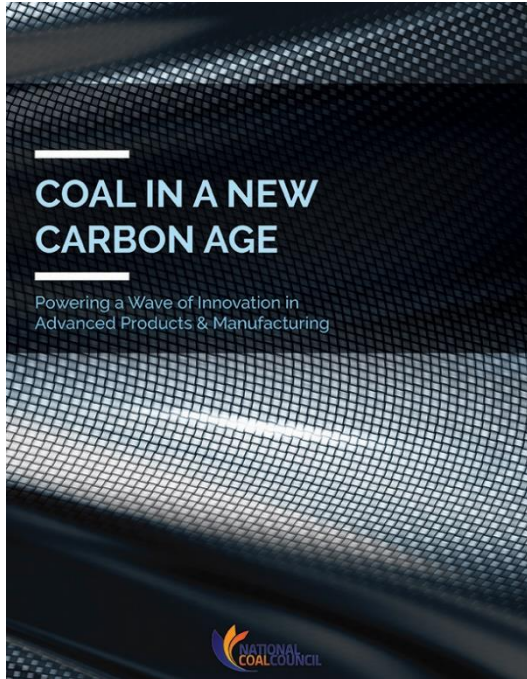
Deck Slone
National Coal Council Chair 2018-2019



Randall Atkins
National Coal Council Vice Chair 2019-2020
Chair – Coal in a New Carbon Age Report



S u m m a r y



Secretary Perry's Request

"... develop a white paper assessing opportunities to enhance the use of U.S. coal beyond power markets ... focus on new markets for 'coal products' including coal conversion ... carbon engineered products ... rare earth elements ... coal combustion products ... biotechnology approaches ... and beneficiated coal ..."

Key Questions Addressed

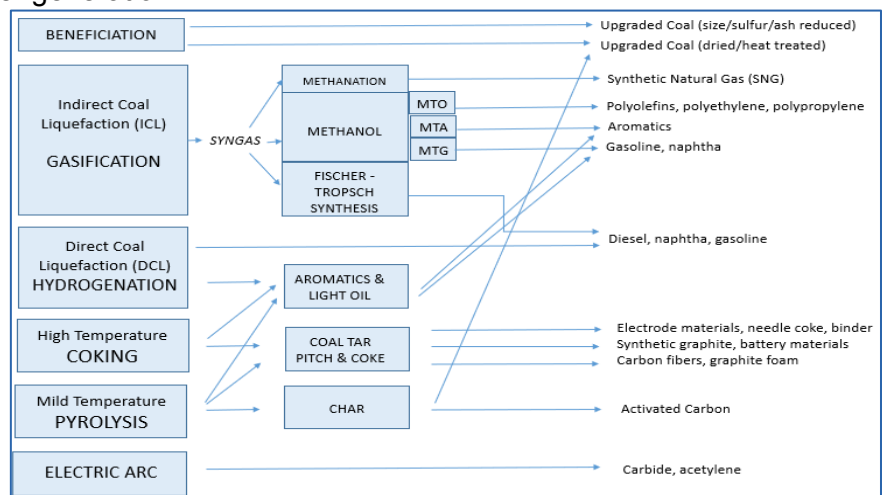
- ~ What significant market-scale opportunities exist for new markets for coal?
- ~ What are the economic, energy security, trade and other issues the U.S. faces now that can be addressed with new markets for coal?

Strategic Objective

The United States is embarking on a "New Age of Carbon" which will usher in significant opportunities for coal beyond conventional markets for power generation and steelmaking. Coal, with its inherent carbon content, is on the crest of powering a wave of innovation in advanced products and manufacturing.

Principal Findings

- The opportunity represented by coal-to-products markets is compelling. The U.S. currently produces about 750 million tons of coal per year, more than 90% of which is used for power generation. The global market for coal-to-products is estimated to consume 300-400 million tons of coal annually. Utilization of domestic U.S. coal for coal-to-products applications has the potential to be on the same order of magnitude as that projected for coal power generation applications.
- Coal-to-products markets create associated and additive economic and social benefits in the form of new mining and manufacturing jobs, especially in regions of the U.S. adversely impacted by the recent downturn in coal production and power generation.
- Coal-to-products markets support and enhance U.S. environmental objectives through their unique performance characteristics. Criteria and CO₂ emissions reductions are achieved by utilizing coal as an alternative to high-emitting processes/products, through use of coal to create durable, light-weight carbon products for aerospace and automotive industries with the potential for corresponding fuel reduction, and by using coal to create sorbents that capture CO₂ from fossil power plants. Coal is also used to create high-strength composite materials and rare earth element components for the wind and solar power industries.

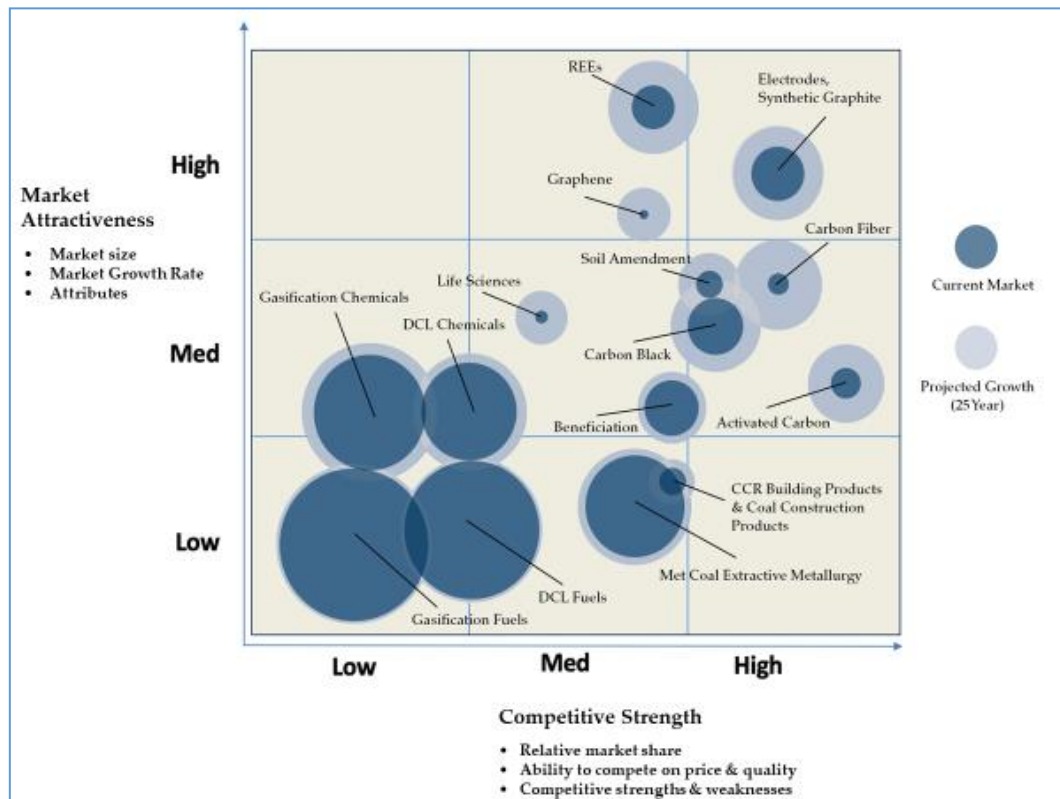


Market Assessment

The NCC's report assesses market-scale opportunities to enhance the use of U.S. coal in various coal-to-products markets. The technologies and market sectors addressed in the report include coal beneficiation; coal to liquid fuels, natural gas and chemicals; coal to carbon products, such as activated carbon, carbon fibers, graphite, graphene, carbon foam and carbon black; rare earth elements; and life science/medical, bio-tech and agricultural uses.

An assessment prioritizing opportunities for development and commercialization of these markets was conducted using a nine-block analysis gauging market attractiveness and competitive strength. The resultant outlook details pathways in three primary categories:

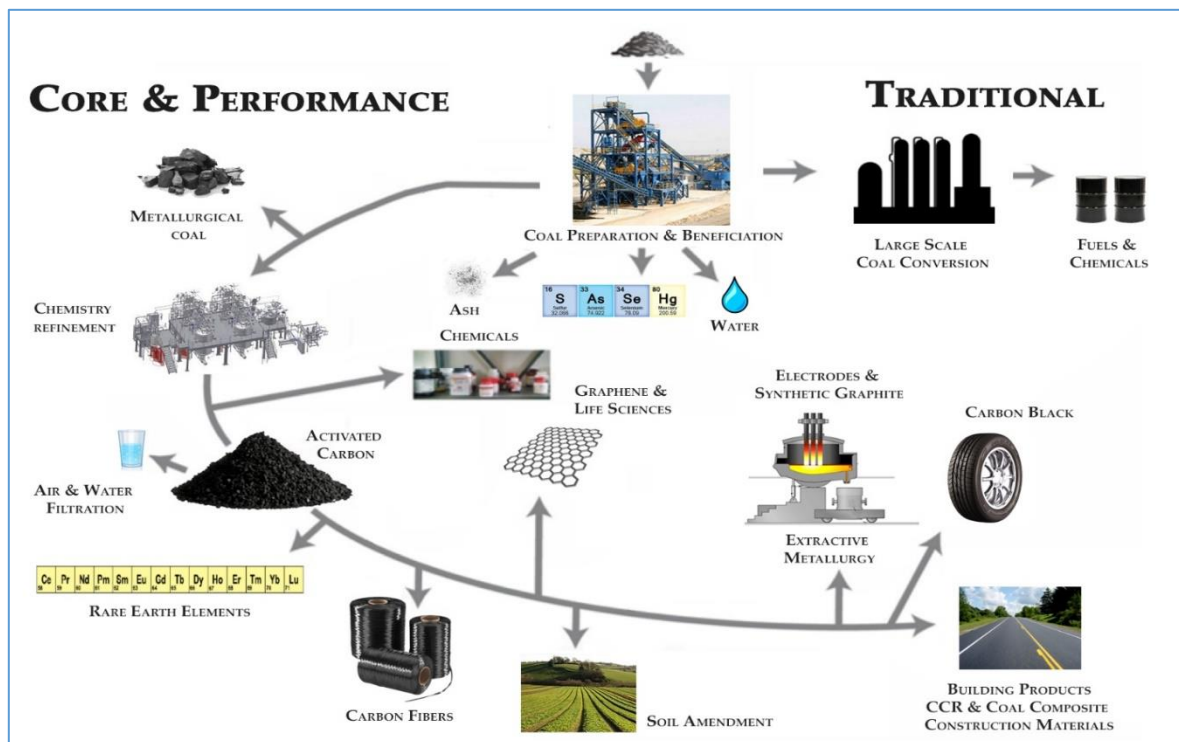
- **TRADITIONAL** – Low Market Attractiveness-Low Competitive Strength
This sector is characterized by high commodity volumes, technically and technologically proven, requiring high capital expenditures and providing marginal economic opportunity in the U.S. due to competition from other resources. Products in this category include bulk chemicals and fuels.
- **CORE** – Medium Market Attractiveness-High Competitive Strength
This sector is characterized by moderate industrial-scale volumes, technically proven, requiring moderate capital expenditures and providing a sizeable opportunity in the U.S. Specialized products in this category include extractive metallurgy, coal beneficiation, activated carbon, carbon black and coal-derived building products.
- **PERFORMANCE** – High Market Attractiveness-High Competitive Strength
This sector is characterized by specialty volumes of high-performance materials utilizing coal's inherent and unique chemistry advantages, optimistically poised for rapid commercialization from small-scale modular to larger industrial scale. Products in this category include rare earth elements, carbon fiber, synthetic graphite and electrodes, graphene, soil amendments and life-science biosensors.



Principal Recommendations

The NCC recommends three primary strategic objectives be pursued by the U.S. Department of Energy to ramp up U.S. manufacturing of coal-derived solid carbon products, chemicals, fuels and rare earth elements.

- **Establish a focused R&D program on coal-to-products.**
Additional research and development (R&D) is needed to achieve commercially viable technical performance-to-cost ratios for the manufacture of coal-derived solid carbon products, chemicals, fuels, and REEs in the U.S.
- **Accelerate research-to-commercial deployment in coal-to-products markets.**
Competing successfully in a global economy requires that the U.S. bring new technologies and related manufacturing to market much faster via replicable modular systems. To avoid being out-paced by other countries, gaps in funding and delays in progression from research to commercial deployment, including new-skills workforce development, must be eliminated.
- **Incentivize private sector investment in coal-to-products production and manufacturing sectors.**
Efficient use of public and private sector financial capital requires alignment of private sector interests and investment readiness with government public sector R&D and economic development investment plans, as well as with defense procurement schedules. Steps must be taken to establish a stronger private sector investment appetite for first-of-a-kind (FOAK) and subsequent single-digit coal conversion plants and end-product factories, in order to quickly move DOE supported coal-to-products technologies into commercial operation, to create jobs and to improve U.S. balance of trade.



Coal in a New Carbon Age Report

<https://www.nationalcoalcouncil.org/page-NCC-Studies.html>

Actions to Advance U.S. Coal-to-Products Markets & Technologies

Strategic Objective:

Establish a focused R&D program on coal-to-products.

- Establish a national R&D program for advanced carbon products and manufacturing within the U.S. Department of Energy.
- Sustain a multi-decade base level of Federal commitment and support.
- Implement a broad-based interagency coordinated program to accelerate coal to fuels and products development.
- Elevate the priority of and increase R&D funding for coal-to-products technologies.

Strategic Objective:

Accelerate research-to-commercial deployment in coal-to-products markets.

- An Office of Carbon Products within the U.S. Department of Energy would establish the required national commitment and empower DOE program managers to pursue the strategic objectives and achieve the desired economic growth, job creation and national security benefits. An Office of Carbon Products would be tasked with building one or more Carbon Advanced Material, Manufacturing and Production (CAMP) centers at coal mining sites in key coal states to accelerate the pace of research-to-commercial deployment of coal-to-products and to develop repeatable modular plant designs.
- Support multiple first-of-a-kind projects throughout the U.S.
- Expand DOE Loan Guarantee Program.
- Dramatically reduce DOE Loan Guarantee Program costs, red tape and processing time.
- Apply U.S. Department of Defense Manufacturing Readiness Levels to DOE programs.
- Target defense applications and national critical materials to avoid “Valley of Death” stall-out.
- Target dual-use applications to quickly grow markets and demand for coal.
- Ensure U.S. developed technologies are deployed in the U.S.
- Address U.S. Export Administration Regulations (EAR) and International Traffic in Arms Regulations (ITAR).

Strategic Objective:

Incentivize private sector investment in coal-to-products production and manufacturing sectors.

- Establish public-private partnerships.
- Provide tax and other investment incentives and subsidies to facilitate the rapid development and commercialization of coal-to-carbon products.
- Validate revenue and business models and management strategies in addition to technology performance and cost.
- Expedite environmental and permit approvals.
- Analyze the condition and suitability of existing infrastructure assets.
- Use shuttered and producing mines, coal power plants and coal communities as economic revitalization zones for new coal to fuels and products production and manufacturing centers.
- Update regulations, legislation and permitting.
- Provide DOE financial support for pre-FEED and FEED projects.

National Coal Council

202-756-4524 – info@NCC1.org – www.NationalCoalCouncil.org



Full Report



COAL IN A NEW CARBON AGE
POWERING A WAVE OF INNOVATION IN
ADVANCED PRODUCTS & MANUFACTURING

National Coal Council Draft Report

May 2019

The National Coal Council is a Federal Advisory Committee established under the authority of the U.S. Department of Energy. Individuals from a diverse set of backgrounds and organizations are appointed to serve on the NCC by the U.S. Secretary of Energy to provide advice and guidance on general policy matters relating to coal and the coal industry. The findings and recommendations from this report reflect a consensus of the NCC membership, but do not necessarily represent the views of each NCC member individually or their respective organizations.



Coal in a New Carbon Age

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NCC Overview – 1984 | 2019

In the fall of 1984, Secretary of Energy Don Hodel announced the establishment of the National Coal Council (NCC). In creating the NCC, Secretary Hodel noted that “The Reagan Administration believes the time has come to give coal – our most abundant fossil fuel – the same voice within the federal government that has existed for petroleum for nearly four decades.”

The Council was tasked to assist government and industry in determining ways to improve cooperation in areas of coal research, production, transportation, marketing and use. On that day in 1984, the Secretary named 23 individuals to serve on the Council, noting that these initial appointments indicate that “the Department intends to have a diverse spectrum of the highest caliber of individuals who are committed to improving the role coal can lay in both our Nation’s and the world’s energy future.”

Throughout its 35-year history, the NCC has maintained its focus on providing guidance to the U.S. Secretary of Energy on various aspects of the coal industry. NCC has retained its original charge to represent a diversity of perspectives through its varied membership and continues to welcome members with extensive experience and expertise related to coal.

The NCC serves as an advisory group to the Secretary of Energy chartered under the Federal Advisory Committee Act (FACA). The NCC is incorporated as a 501c6 non-profit organization in the State of Virginia. Serving as an umbrella organization, NCC, Inc. manages the business aspects of running the Council.

The Council’s activities include providing the Secretary with advice on:

- Federal policies that directly or indirectly affect the production, marketing and use of coal;
- Plans, priorities and strategies to address more effectively the technological, regulatory and social impact of issues relating to coal production and use;
- The appropriate balance between various elements of Federal coal-related programs;
- Scientific and engineering aspects of coal technologies, including coal conversion, utilization or environmental control concepts; and
- The progress of coal research and development.

The principal activity of the NCC is to prepare reports for the Secretary of Energy. The NCC’s members, Executive Committee, Chair’s Leadership Council and Coal Policy Committee develop prospective topics for the Secretary’s consideration as potential subjects for NCC reports. During its 35-year history, the NCC has prepared more than 35 studies for the Secretary, at no cost to the Department of Energy. All NCC studies are publicly available on the NCC website.

The NCC is a totally self-sustaining organization; it receives no funds from the Federal government. The activities and operations of the NCC are funded solely from member contributions, the investment of Council reserves and generous sponsors.



The Secretary of Energy
Washington, DC 20585

August 31, 2018

Mr. Deck Slone
Chairman, The National Coal Council
1000 Independence Avenue SW, Room 4G-036
Washington, DC 20585

Dear Chairman Slone:

I am writing today to request the National Coal Council (NCC) develop a white paper assessing opportunities to enhance the use of U.S. coal beyond power markets.

The white paper should focus on new markets for “coal to products” including coal conversion (coal to liquids, coal to gas, coal to chemicals); carbon engineered products (value-added non-Btu products); rare earth elements; coal combustion products, methanol; biotechnology approaches (agriculture, liquid fuels); and beneficiated coal for non-power uses, among others.

The key questions to be addressed include:

- What significant market-scale opportunities exist for new markets for coal?
- What are the economic, energy security, trade, and other issues the U.S. faces now that can be addressed with new markets for coal?
- Considering the current uses for coal overseas (syngas, chemicals, synthetic oil, transportation fuels, etc.), where and how are these markets operating today and what is the outlook for these markets going forward?
- What has been the domestic history of coal utilization and what can be learned from past successes/failures in coal utilization?
- How can domestic markets for utilization (other than for CO₂) be developed similar to those underway in other countries?

The white paper should be managed under the auspices of the Executive Advisory Board within the NCC. I ask that the white paper be completed no later than April 12, 2019.

Upon receiving this request and establishing your internal working groups, please advise me of your schedule for completing the white paper. The Department looks forward to working with you in this effort.

Sincerely,

Rick Perry

Rick Perry



COAL IN A NEW CARBON AGE

POWERING A WAVE OF INNOVATION IN ADVANCED PRODUCTS & MANUFACTURING

Executive Summary

The United States is embarking on a “New Age of Carbon” which will usher in significant opportunities for coal beyond conventional markets for power generation and steelmaking. Coal, and the carbon it contains, is on the crest of powering a wave of innovation in advanced products and manufacturing.

Advanced markets for coal-derived products, materials and technologies, referenced in this report as “coal-to-products,” include:

- Coal to Liquids – fuels and chemicals
- Coal to Solid Carbon Products – carbon fiber, activated carbon, graphite, electrodes, graphene, building and construction products, carbon foam and carbon black
- Rare Earth Elements – component minerals for health care, military, transportation, power generation, petroleum refining and electronics applications
- Coal Beneficiation – quality enhancements to coal for specialty product applications
- Life Science, Biotech and Medical – prosthetics and biosensors
- Agricultural Uses – fertilizer

The opportunity for the U.S. represented by these markets is compelling. Advancing new markets for coal can enhance U.S. national defense security, bolster the nation’s energy and mineral security, enhance our nation’s environmental objectives and contribute to America’s economic prosperity.

Economic Benefits – Currently, the global market for coal-to-products is estimated to consume between 300-400 million tons per year of coal, mostly in the areas of chemicals, fuels and fertilizers in emerging economies. As a frame of reference, the U.S. produced roughly 750 million tons of both thermal and metallurgical coal in 2018. In many advance market applications, coal is less expensive (\$12-\$50/ton) than traditional feedstocks such as petroleum (\$400-\$500/ton), offering opportunities for both reducing the cost of manufacturing carbon products as well as, in many cases, providing a superior quality carbon feedstock.

The analysis undertaken by the National Coal Council (NCC) for this report, indicates that coal tonnage utilization of domestic U.S. coal for coal-to-products applications has the potential to be on the same order of magnitude as that projected for coal power generation applications in the coming years. The markets for carbon products, in particular, are growing at attractive above average metrics of an approximately 18% compounded annual growth rate (CAGR).

Social Benefits – The economic growth potential of coal-to-products provide social benefits in the form of new mining and manufacturing job creation, especially in regions of the country adversely impacted by the recent downturn in coal production and power generation. Indeed, many future coal-to-product manufacturing sites might be advantaged to be located in repurposed areas of former mining production to take advantage of both coal feedstocks and logistical economies.

Additional social benefits accrue through the use of advanced medical products that improve patient care, early disease diagnosis and pathogen detection. Coal-derived agricultural products enhance water retention, growth of beneficial micro-organisms, root growth and plant yield.

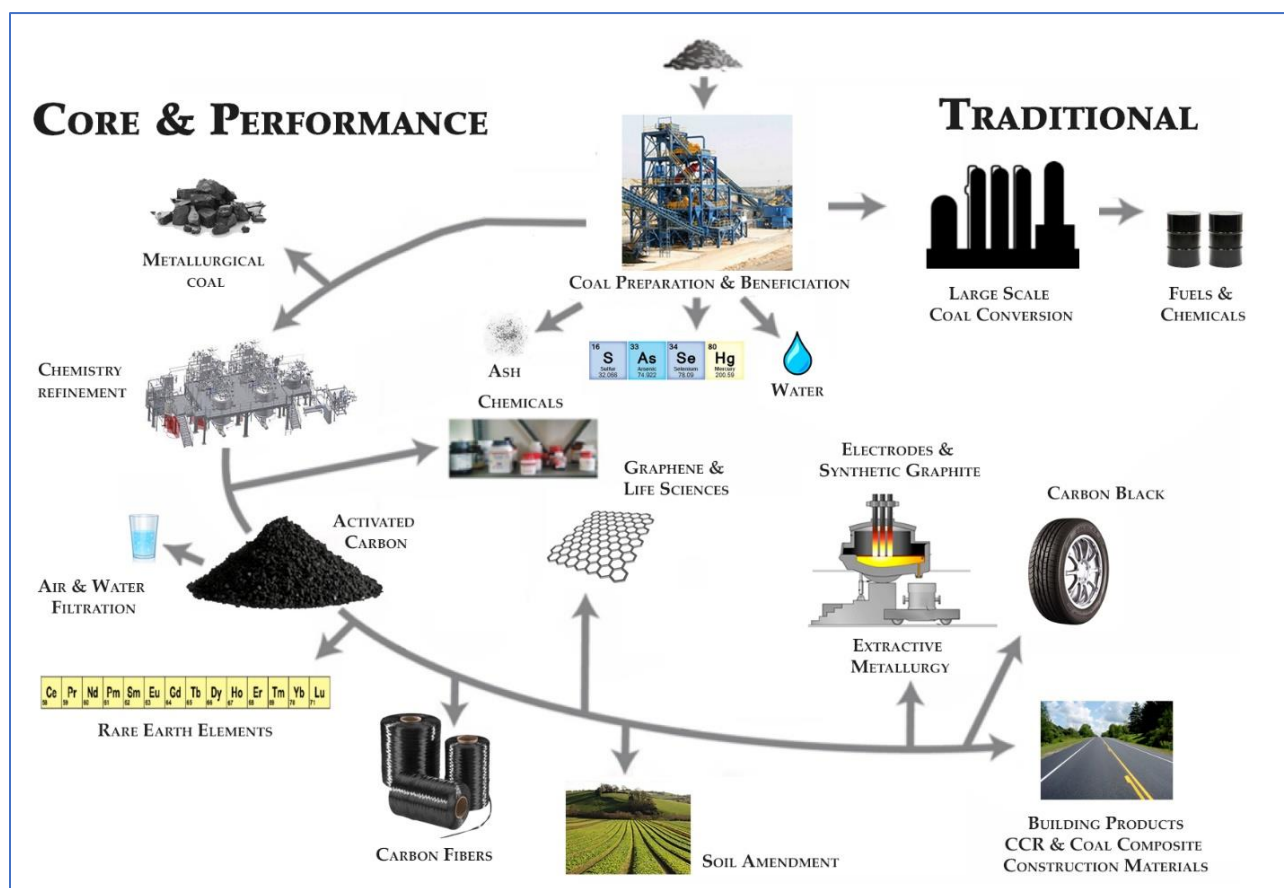
Environmental Benefits – Coal-to-products support and enhance our nation's environmental objectives through their unique performance characteristics. Advanced forms of carbon now serve as key building blocks for a host of new solutions that result in cleaner energy, cleaner water and cleaner air. These benefits are realized 1) through the potential widespread alternative uses of coal that do not have the same carbon emission characteristics as other current uses; 2) through the use of coal to create durable, light-weight carbon products for the aerospace and automotive industries with the potential for a corresponding reduction in fuel use because of lightweighting; 3) through the use of coal to create high-strength advanced composite materials and high-efficiency rare earth element components for the wind and solar power industries; 4) through the use of coal to create sorbents used to capture CO₂ from fossil fuel power plants, cement kilns and industrial sources; 5) through the use of sorbents for water purification, and 6) through the use of coal to create composite products for infrastructure, concrete and building materials.

National Security Benefits – Rare earth elements support critical sectors of the U.S. defense industry. Advancing domestic market production of these critical minerals from coal and coal ash could greatly reduce the nation's nearly 100% dependence on imports from China.

To capitalize on the significant opportunity afforded by these new markets for coal, the National Coal Council undertook a systematic approach for characterizing, assessing and prioritizing market and product attractiveness using a nine-block analysis. Each of the coal-to-products markets was assessed based both on their market attractiveness (market size, market growth rate, attributes) and competitive strength (relative market share, ability to compete on price and quality, competitive strengths and weaknesses). This resultant analysis details pathways in three primary categories:

- **TRADITIONAL** – Low Market Attractiveness-Low Competitive Strength
This sector is characterized by high commodity volumes, technically and technologically proven, requiring high capital expenditures and providing marginal economic opportunity in the U.S. due to cost competition from other resources, specifically lower cost natural gas and petroleum feedstocks. Products in this category include bulk chemicals and fuels.

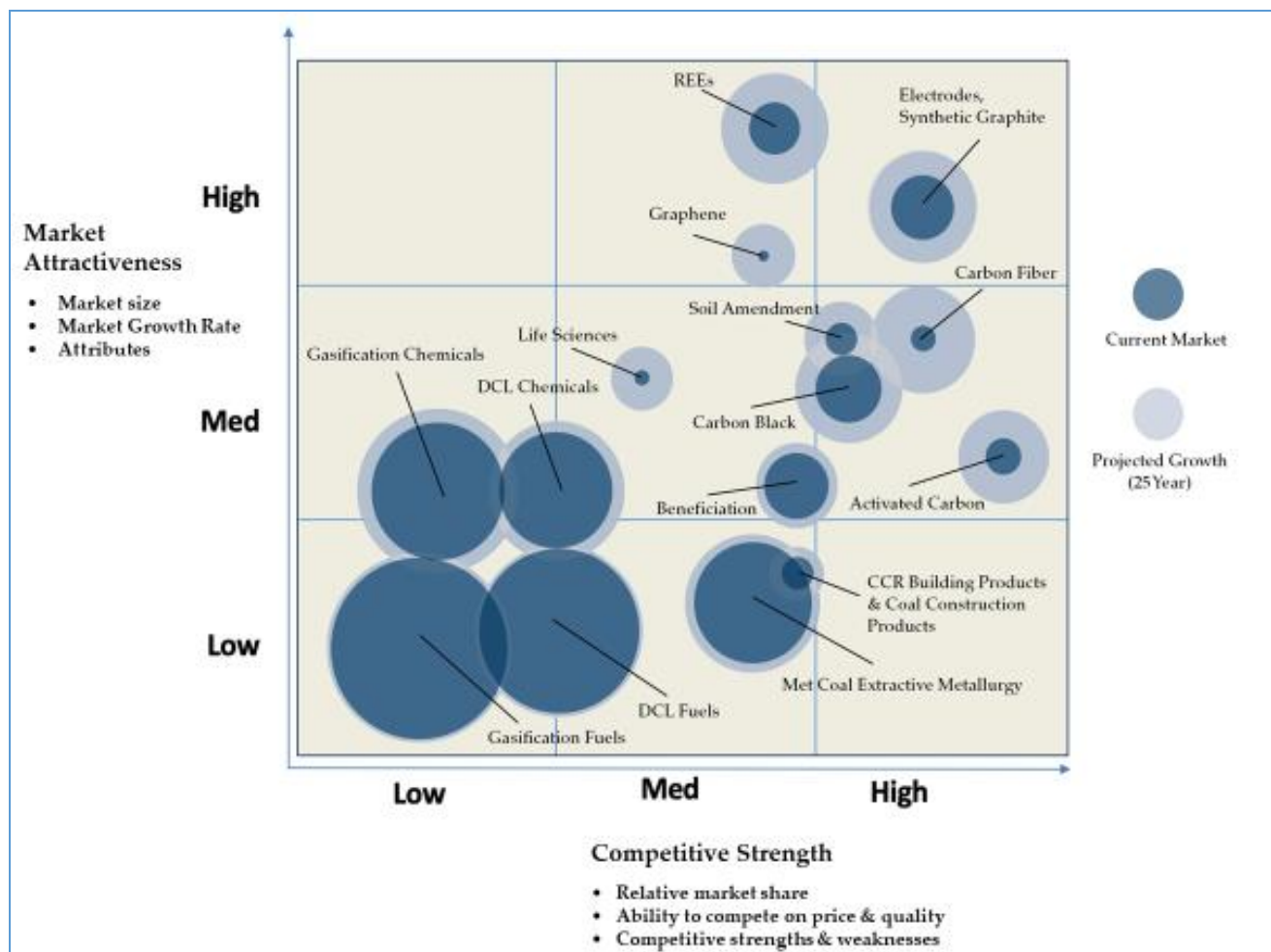
- CORE – Medium Market Attractiveness-High Competitive Strength**
 This sector is characterized by moderate industrial-scale volumes, technically proven, requiring moderate capital expenditures and providing a sizeable opportunity in the U.S. Specialized products in this category include extractive metallurgy, coal beneficiation, activated carbon, carbon black and coal-derived building products.
- PERFORMANCE – High Market Attractiveness-High Competitive Strength**
 This sector is characterized by specialty volumes of high-performance materials utilizing coal's inherent and unique chemistry advantages, optimistically poised for rapid commercialization from small-scale modular to larger industrial scale. Products in this category include rare earth elements, carbon fiber, synthetic graphite and electrodes, graphene, soil amendments and life-science biosensors.



Non-Conventional Uses of Coal:
CORE & PERFORMANCE routes (left and lower) and **TRADITIONAL** routes (upper right)

The conclusions of the NCC's nine-block analysis shown below provide a qualitative, directional assessment of market opportunities. As graphically represented, the analysis depicts each data point with two concentric bubbles. The size of the darker blue inner bubble is a qualitative representation of the total size of the market (in annual revenues) that coal is able to address; the size of the lighter blue outer bubble is a qualitative representation of potential market growth over the next 25 years.

Based on NCC's nine-block analysis, the most significant growth opportunities for U.S. coal are in producing high-value specialty materials and products at reduced costs that will accelerate growth and spearhead large-scale applications. This could constitute a step-change in turning coal into the future 'carbon ore' mineral asset. Coal could become a new, innovative, low-cost solution to creating advanced materials and products across many important sectors, including automotive, aerospace, construction, electronics, low carbon energy, agricultural, environmental and life sciences.



In his request to the NCC, Secretary of Energy Rick Perry asked how domestic markets for coal-to-products could be developed and commercialized in the U.S. The NCC recommends three primary strategic objectives be pursued by the U.S. Department of Energy to accelerate U.S. manufacturing of coal-derived solid carbon products, chemicals, fuels and rare earth elements.

- **Establish a focused R&D program on coal-to-products.**
Additional research and development (R&D) is needed to achieve commercially viable technical performance-to-cost ratios for the manufacture of coal-derived solid carbon products, chemicals, fuels, and REEs in the U.S.
- **Accelerate research-to-commercial deployment in coal-to-products markets.**
Competing successfully in a global economy requires that the U.S. bring new technologies and related manufacturing to market much faster via replicable modular systems. To avoid being out-paced by other countries, gaps in funding and delays in progression from research to commercial deployment, including new-skills workforce development, must be eliminated.
- **Incentivize private sector investment in coal-to-products production and manufacturing sectors.**
Efficient use of public and private sector financial capital requires alignment of private sector interests and investment readiness with government public sector R&D and economic development investment plans, as well as with defense procurement schedules. Steps must be taken to establish a stronger private sector investment appetite for first-of-a-kind (FOAK) and subsequent single-digit coal conversion plants and end-product factories, in order to quickly move DOE supported coal-to-products technologies into commercial operation, to create jobs and to improve U.S. balance of trade.

Specific tactics to achieve these objectives are detailed in Chapter 3 of this report.

The nation's abundant coal resources are well-suited to securely support the U.S. as it enters the New Carbon Age, powered by innovation in both advanced products and manufacturing.

Chapter 1. Overview of Opportunities for Coal-to-Products*

Introduction

The United States is embarking on a “New Age of Carbon” which will usher in significant opportunities for coal beyond conventional markets for power generation and steelmaking. Coal, and the carbon it contains, is on the crest of powering a wave of innovation in advanced products and manufacturing.

The opportunity for the U.S. represented by these markets is compelling. The market landscape is an evolving mosaic of products, covering everything from undifferentiated commodities to advanced nano-carbon structured specialties, ranging from multi-billion-dollar coal conversion systems to novel single-use hand-held biosensors.

Currently, the global market for coal-to-products (including fuels, chemicals and carbon products) is estimated to consume between 300–400 million tons per year of coal.ⁱ As a frame of reference, the U.S. produced roughly 750 million tons of both thermal and metallurgical coal in 2018. The analysis undertaken by the National Coal Council (NCC) for this report indicates that utilization of domestic U.S. coal for coal-to-products applications has the potential to be on the same order of magnitude as that projected for coal power generation applications.

In addition, most of the coal-to-products considered in this report create associated and additive economic opportunities by providing secure, domestic feedstocks to support industry. The economic growth potential of coal-to-products provide social benefits in the form of new mining and manufacturing job creation, especially in regions of the country adversely impacted by the recent downturn in coal production and power generation. The markets for carbon products, in particular, are growing at attractive above average rates of approximately 18% compound annual growth rate (CAGR), based on 2011-2018 data presented in Table 2.2 of this report.

Coal-to-products also support and enhance our nation’s environmental objectives through their unique performance characteristics. A host of newly emerging and existing coal-to-carbon product technologies are changing the way energy is generated, used and conserved. Advanced forms of carbon now serve as key building blocks for a host of new solutions – including cleaner energy, cleaner water and cleaner air – that will benefit our society and our economy. Criteria and CO₂ emissions reductions are achieved 1) overall through the potential widespread use of coal in alternative uses that do not have the same carbon emission characteristics as other current uses; 2) through the use of coal to create durable, light-weight carbon products for the aerospace and automotive industries with the potential for corresponding fuel reduction; 3) through the use of coal to create high-strength advanced composite materials and high-efficiency rare earth element components for the wind and solar power industries; 4) through the use of coal to create sorbents used to capture CO₂ from fossil fuel power plants, cement kilns and industrial sources; and 5) through the use of coal to create composite products to be used in infrastructure, concrete and building materials.

* The term “coal-to-products” as used throughout this report refers to coal-derived products, materials and technologies beyond conventional markets for coal in power generation and steelmaking.

To grapple with the strategic perspectives and with the main objective of developing a coherent outlook, a systematic approach for characterizing and prioritizing opportunities was chosen as a means of mapping out “directional opportunities.” The chosen tool was the GE-McKinsey nine-block frameworkⁱⁱ. The approach recognizes the complexities of comparing a diverse portfolio of business units – in this case a diverse set of product opportunities – and resolves the challenges of putting everything on the same basis by considering two common features; namely, *market attractiveness* and *competitive strength*. The results of this analysis are shown below in Figure 1.1. Additional supporting commentary is presented in Chapter 2.

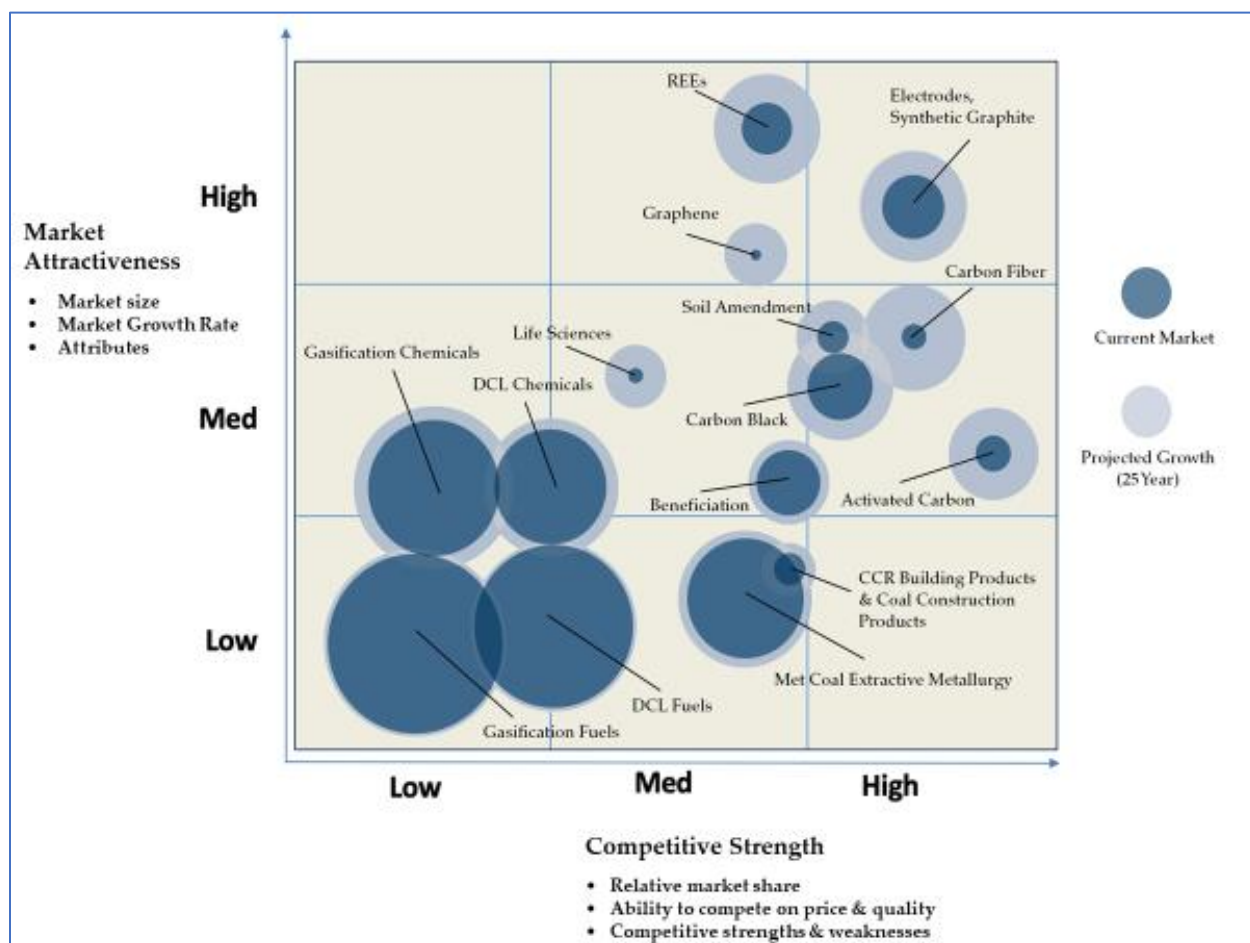


Figure 1.1 A Nine-Block Depiction of the Main Coal-to-Product Technology-Market Pathways

Additional considerations for these market opportunities also include:

- Arbitrage between the Price of Coal and Petroleum in Carbon-related Products. Both a ton of coal and a ton of petroleum each contain roughly 70% carbon matter. A ton of thermal coal, however, sells for between \$12 and \$50 in the U.S., while a ton of petroleum sells for roughly \$400-\$500.

- China already has a strong foothold in some of these markets. Should the U.S. stand idly by, American carbon product producers and manufacturers may not win the global battle to lead in the New Carbon Age. Should that happen, China could control more than half of the world's supply of advanced carbon products, including batteries, graphene sensors, graphite, carbon fibers and other strategically important products. China would once again have the potential to disrupt supply chains and free-market pricing for strategically important solid carbon materials, as that nation already did before with rare earth elements (REEs).

These coal-to-products opportunities should be enhanced, encouraged, invested in, developed and fully commercialized in the U.S. They hold the promise of not simply replicating China's or other countries' gasification-based coal economy, but of initiating a new and different carbon-based technology and carbon manufacturing renaissance in the U.S.

At the request of U.S. Secretary of Energy, Rick Perry, the National Coal Council (NCC) is providing this assessment of opportunities to enhance the use of U.S. coal in various coal-to-products markets. This report identifies:

- Significant market-scale opportunities that exist for new markets for coal.
- Employment, economic, energy security, trade and other issues the U.S. now faces that can be addressed with new markets for coal.
- Objective criteria that can be employed to assess new opportunities, including:
 - Market readiness
 - Market acceptance
 - Technology readiness
 - Economic and investment feasibility
 - Environmental and sustainability market acceptance

New and pre-existing markets for coal are being pursued worldwide for a host of applications. Countries such as China, Korea, South Africa and Japan who are not endowed with significant oil and gas reserves are already pursuing conversion of coal to synthetic oil, transportation fuels, synthesis gas (syngas), hydrogen and industrial chemicals. They are doing so at full industrial scale using more than 300-400 million tonsⁱⁱⁱ of coal per year.

In the U.S., efforts are already underway to convert coal into advanced materials, such as carbon fibers (that can be used in aerospace, infrastructure, automotive and energy applications), carbon resins (which can be used in advanced manufacturing such as 3D printing), basic building materials (such as roads, roofing, rebar and infrastructure) and even life-science applications (such as diagnostic sensors and personalized medicine). Numerous initiatives are also being pursued in the U.S. to convert coal into cleaner and greener transportation fuels, such as low sulfur diesel and naphtha.

Coal has significant potential beyond its use to fuel power plants or produce steel. Advancing new markets for coal can enhance U.S. national defense security, bolster our nation's energy and mineral security, and contribute to our economic prosperity.

The Value of Advancing New Markets for Coal

Why examining opportunities for coal-to-products is not only important but essential?

- New and existing opportunities must not be lost for a host of reasons, including national employment, energy security, defense, economic, competitive, technological, trade and financial reasons.
- Our vital coal industry has been severely hampered over the past decade by regulatory and market competitive pricing pressures and the thermal coal markets are in pronounced decline. Non-conventional uses of coal offer the opportunity to revitalize and transform both the thermal and metallurgical coal industries in America.
- This report demonstrates that taking advantage of two significant resources in the U.S. – its people and its coal – can contribute greatly to both our nation's materials and manufacturing future, as well as to its economic vitality over the next century.

What are the opportunities for coal-to-products markets and technologies?

- This report details prior efforts and activities in the U.S. to develop non-conventional uses for domestic coals. The U.S. Department of Energy (DOE) has supported substantial advancements in sciences and technologies that provide the foundation to establish coal-to-products industries that can support numerous jobs in the distressed coal mining communities throughout the U.S.
- The report also details the use of coal for a wide range of productive uses being pursued internationally. Roughly 300-400 million tons^{iv} of coal are used every year outside of the U.S. for the production of goods rather than power.
- The U.S. has an opportunity to establish a global leadership role in areas of production and market sectors in which our nation has clear material advantages.
- Low-priced natural gas and low-priced heavy oil can be used as a productive co-feedstock with coal in the production of highly valued-added products. Certain carbon-based products offer opportunities to blend America's cheap and plentiful natural gas and oil in the production of undifferentiated commodity fuels and solid carbon material products.
- This report further details the wide range of technologies and the techno-economic outlook for those technologies here in the U.S. These include:
 - Coal conversion technologies and beneficiation/upgrading processes (coal to liquids, coal and gas/CO₂ to liquids, carbon fibers, resins and chemicals, and precursor compounds used to make advanced carbon materials)
 - Non-combustion products (building products, infrastructure uses) and advanced materials from coal (including carbon fiber, graphite, graphene, carbon nanotubes, and activated carbon)
 - Rare earth elements (REEs) from coal, ash and coal overburden
 - Coal combustion products (CCPs)
 - Life science and medical uses (possible collaboration with NIH)
 - Biotechnology and agricultural applications

Each of these areas represents a considerable opportunity for American enterprise and the U.S. economy, as well as a significant opportunity for the U.S. coal industry to bolster production to serve those markets, be they domestic or international.

Who may benefit by taking advantage of the coal-to-products opportunities that exist?

- The U.S. coal-to-products opportunity is a win-win landscape benefitting both new and existing market sector participants.
- Use of coal for the purposes detailed in this report will benefit coal miners, coal mining communities, domestic manufacturing and the American economy, strengthen our international competitiveness and help secure America's role as a global leader in the coming 21st century's Carbon Age where carbon-based advanced materials (carbon fiber, carbon nanotubes, carbon dots, graphene, graphite etc.) and carbon-based lightweight manufacturing is poised to dominate industry.
- There are also secondary and tertiary benefits associated with increased utilization of coal for the purposes detailed in this report. For example, the transportation industry will benefit from increased utilization of new carbon materials with less weight which can be used in the construction of more efficient vehicles for road, rail, water and air transportation. Mine-site carbon product manufacturing will not only improve the economics and logistics of the U.S. coal industry, but will revitalize communities that have been negatively impacted by the recent downturn in U.S. coal demand and production. Developing robust coal-to-products industries will enable our nation to not only bring back mining jobs, but provide former miners with high wage manufacturing jobs.
- Society will also benefit from reduced emissions enabled through the use of durable, light-weight, high-performance, high-efficiency coal-derived advanced carbon products used in aerospace, automotive, renewable energy, construction and other industries, as well as in new medical, technical and advanced manufacturing applications.
- Due to the compositional and chemical differences between coal and other carbon-based feedstocks, such as oil and gas, there are uses where one feedstock has inherent advantages over the other. The increased use of coal for carbon-based product manufacturing will leverage the respective strengths of our nation's vast coal, oil and gas feedstocks to achieve the best overall economic competitive position for the U.S.

Where will the benefits of increased utilization of coal-to-products be realized?

- Geographically, the greatest initial benefit of the increased use of coal for products will be felt in those areas of the U.S. that have been most adversely impacted by the downturn in coal production and coal power generation.
- These impacted states have historically been some of the strongest contributors to the nation's economic growth. The opportunity exists to revitalize and reinvigorate these local economies by developing coal-to-products manufacturing industries at the sites of many now shuttered facilities.
- Unemployment in these areas remains well above national averages and provides one of the few areas in the U.S. where capable workers, abundant inexpensive land and underutilized industrial facilities are available.

How could the U.S. Department of Energy and the U.S. government work together with industry to accelerate deployment of coal-to-products technologies?

The NCC recommends three primary strategic objectives which could be pursued by the Department of Energy, in concert with private industry, to accelerate U.S. manufacturing of coal-to-products, including coal-derived solid carbon products, chemicals, fuels and rare earth elements.

- Establish a dedicated Research and Development (R&D) program within the U.S. Department of Energy focused on coal-to-products, in a way that builds upon the centers of excellence that DOE already has established for both carbon products and their critical uses in energy efficiency programs.
- Accelerate research-to-commercial manufacturing deployment in coal-to-products market sectors.
- Incentivize private sector investment in coal-to-products sectors.

In Chapter 3 of this report, the NCC details specific approaches and tactics to achieve these strategic objectives in an effort to encourage, enhance and accelerate the commercialization of coal-to-products markets. Many of these tactics are based on an examination of international developments in coal-to-products markets and on lessons learned from previous initiatives undertaken in the U.S.

Specific to the U.S., there have been a number of historic coal upgrading and coal conversion projects that were proposed and developed to various stages before ultimately being suspended. The obstacles that derailed these projects were predominantly some combination of the following:

- Successful financing of coal conversion projects requires a level of certainty regarding sustained long-term (20+ years) price differentiation between coal and competitive oil or natural gas feedstocks to offset inherently higher capital costs associated with handling, transporting and converting a solid feedstock (coal) into a gas or liquid.
- Delays due to obtaining project financing and/or environmental and construction permits that tend to drive up overall costs, causing the commercialization process to go through multiple re-evaluations with resultant cost escalation.
- First-of-a-kind (FOAK) development and deployment risks tend to lead to extra mitigation costs that can ultimately cause projects to become non-viable.
- Coal conversion projects tend to be large in scale and cost and can take a number of years to proceed through development, engineering and design, permitting, financing, construction and startup. It is not unusual for market conditions to change during such extended time periods, which may lead to reassessment of, and changes to, overall project attractiveness. It may also be difficult to maintain the commitment and momentum of project owners/developers over such extended timeframes.

- Companies driving new advanced technologies into markets that may also be new to them, such as coal companies seeking to drive coal products into chemical or carbon fiber markets, may not have the internal expertise, or adequate access to external expertise, needed for such new technology directions.
- Technology hurdles or roadblocks can sometimes occur along the development pathway. These can generally be overcome by dedicated and talented teams of scientists and engineers, although not always in an economically viable manner.

Lessons learned from assessment and analysis of previous U.S. coal upgrading and coal conversion technology development and deployment efforts include the following:

- The most successful efforts have primarily been the result of cooperative partnerships between public entities and private industry.
- Public entities often conduct or support fundamental research that enables private industry to develop and successfully deploy new technology advances into the marketplace.
- First-of-a-kind (FOAK) technology deployments carry risks that are often difficult and costly to mitigate, making it hard for private industry to move such projects forward. Federal assistance to help mitigate such risks can be effective to encourage such projects to move forward.
- Redirection from traditional coal markets to new coal-to-products markets often requires expertise outside that of existing coal-based companies. Universities and federal and state governments and their lab and research facilities can help provide trained and qualified researchers and technologists to fill such needs.
- Coal conversion technologies that can compete with alternative petroleum- or natural gas-based technologies often require some level of value addition to offset inherently higher capital costs due to solids handling of coal and the costs of converting a solid to a liquid or gas. This offset often comes from advantages in the relative raw material costs of coal versus the alternatives. This advantage can come from a differential in relative energy costs (cost per BTU basis), which is often difficult to sustain with adequate certainty over the long (20+ year) financing timeframes of such projects. But it can also be the result of an inherent advantage of coal, such as in the production of products that are heavily dependent on the carbon content of the feedstock (e.g., graphite, graphene, carbon fibers, or carbon-heavy chemicals such as acetyl chemicals) or are dependent on other components that exist in greater levels in coal (such as rare earth elements (REE) or critical minerals (CM)).
- Coal upgrading technologies, if adequately cost and energy efficient, can open up new domestic and export markets for U.S. reserves, for both lower-rank western coals and higher-rank eastern coals.

- As seen from an historical review, federal support for coal upgrading and coal conversion technologies has tended to be cyclical, with various crises or economic or national security concerns serving as primary drivers. Such cyclical efforts can lead to losses of critical expertise and program momentum during periods of reduced support. It is recommended that some base level of federal support be continuously maintained so that critical needs can be addressed more rapidly and more effectively as they arise.
-

The nation's abundant coal resources are well suited to securely support the U.S. as it enters the New Carbon Age, powered by innovations in both advanced products and advanced manufacturing.

Markets for Coal in the New Age of Carbon

Coal-to-products technologies and markets addressed in this report include the following. More detailed descriptions are provided in Appendix A.

Coal Beneficiation – Coal beneficiation relates to the upgrading of coal quality and/or the conversion of coal into higher value products. The three primary technology options for coal upgrading are: (1) physical or gravity separations (e.g., conventional coal preparation); (2) thermal treatment (e.g., coke production); and (3) chemical extraction (e.g., production of low ash carbon products).

Coal to Liquids, Natural Gas and Chemicals – Processes that produce liquid fuels, chemicals, and synthetic natural gas (SNG) from coal can involve prior conversion of the coal to syngas (through coal gasification), a process also known as indirect coal liquefaction (ICL). Cleaned and chemically adjusted syngas can be used as a feedstock for chemical reactions that can produce fuels and chemicals. Among the fuels that can be produced directly are diesel fuel, gasoline and methane (synthetic natural gas). Primary chemicals that can be produced include methanol and ammonia. Methanol can then be converted to higher-value products such as olefins (such as ethylene and propylene), aromatics (such as benzene, toluene and xylene), monoethylene glycol (MEG) gasoline, or dimethyl ether (DME), among others. Ammonia, either itself or following conversion to urea, is a building block for fertilizers for agricultural markets.

Direct coal liquefaction (DCL) involves the solvent extraction of organic material from coal and the hydrogenation of the extracted material. Similar to ICL, DCL can produce fuels (diesel, gasoline, jet fuel) and chemicals (plastics products and synthetic fibers).

Coal to Products – The inherent carbon content of coal lends itself to the use of coal to produce carbon-based products. Current existing applications for carbon products include electrodes, seals, bearings, refractories, fishing rods, golf clubs, nuclear reactors, various automotive materials, and aircraft parts such as the fuselage of the Boeing 787, and increasingly in automotive parts and building materials. Carbon materials are also used in environmental applications, such as the removal of contaminants from water and flue gases (activated carbon) and the purification of municipal drinking water (anthracite filter media).

Detailed descriptions of the following coal-to-products markets are included in Appendix A:

- Electrodes, Graphite Products and Carbon Fibers
- Activated Carbon
- Coal Use in Non-ferrous Metal Smelting
- Coal to Graphene and Carbon Nanotubes
- Coal to Building Products
- Coal to Carbon Foam
- Coal to Carbon Black

Coal Derived Critical Minerals and Rare Earth Elements – Critical minerals (CMs), including rare earth elements (REEs) are used in end products in critical sectors of the U.S. economy that include health care, military, transportation, power generation, petroleum refining, and electronics. Specific clean energy related REE applications include magnets for wind turbines, batteries and vehicles, and phosphors for lighting products.

Metallurgical Coal Sector Use of Coal Products – The term “metallurgical coal” is commonly applied to coal that is used to make coking coal. The resultant coke is used primarily in ironmaking blast furnaces and, to a lesser extent for other iron and steel applications and in non-ferrous extractive metallurgy. However, coal products are used in other metallurgical processes with coking. Two key potential uses for coal in extractive metallurgy are anode coke and needle coke. Activated carbon also finds use in the metallurgical sector.

Life Sciences and Medical Uses – The history of coal in the chemical and pharmaceutical industry can be traced to the discovery and development of synthetic dyes from coal tar – a byproduct of town gas and the steel industry. Modern pharmaceuticals have their origins in apothecaries that commenced to produce and sell drugs extracted from flora and fauna as well as in the organic chemical companies – especially dyestuffs that moved from manufacturing dyes through extraction from coal tar to other organic chemicals, using the organic building blocks extracted from coal and coal byproducts.

Graphene MedTech Uses – Graphene’s unique physical structure, as well as its chemical and electrical properties, make it ideal for use in medical sensor technologies. Several of these platforms have been used to immobilize biomolecules, such as antibodies, DNA and enzymes, to create highly sensitive and selective biosensors with high specificity which can significantly enhance patient care, accurate early diagnosis of diseases and pathogen detection in clinical practice.

BioTech and Agricultural Uses – Lignite contains natural organic compounds known as humate, which derive from the decomposition of plants and are found in soil, peat, as well as lignite. Application of humates to soils is beneficial, promoting increased water retention, growth of beneficial micro-organisms, root growth, and plant yield serving as a source of natural nutrients. Humic acid products could play an important role in counteracting the deterioration of fertile land, a challenge caused by intensive farming, erosion and drought.

Chapter 2. Trends and Future Outlook for New Coal-Derived Products in the U.S.

Key Findings

- **Opportunities exist to use coal more productively beyond its conventional applications in power generation and steelmaking. These new opportunities span a mosaic of products, with the most significant near-term growth potential in the production of high-value specialty materials and products.**
- **Industry analysis tools used to assess the market attractiveness and competitive strength of various markets sectors, indicate the relative value of three classes of products: Traditional (gasification- and liquefaction- derived fuels and chemicals), Core (metallurgical coal/coking, beneficiation, activated carbon, carbon black and building products) and Performance (carbon fibers, graphite, electrodes, graphene, rare earth elements, soil amendments and life science applications).**
- **Today, about 300-400 million tons of coal per year is consumed for non-conventional uses worldwide. The U.S. has an opportunity to take a leadership role in and benefit economically from participation in the anticipated future growth of these new markets for coal.**

Executive Highlights

The importance of coal to the U.S. economy is evolving. A significant opportunity for the U.S. exists to dramatically increase and diversify its coal use beyond conventional electric power generation and coking applications to also include a broad range of coal-to-product categories. The future growth outlook for coal will be tied to new innovations and new advanced product introductions.

Based on the analysis conducted for this report, the most significant growth opportunities for U.S. coal are in producing high-value specialty materials and products at reduced costs that will accelerate growth and spearhead large-scale applications. This could constitute a step-change in turning coal into the future ‘carbon ore’ mineral asset. Coal could become a new, innovative, low-cost solution to creating advanced materials and products across many important sectors – automotive, aerospace, construction, electronics, low carbon energy, agricultural, environmental and even life science sectors.

New opportunities exist for coal to become the precursor for advanced materials to augment or replace steel, aluminum and concrete materials, supplying high volume materials to a broad swath of U.S. industrial sectors.

Introduction and Background

An expanding opportunity for coal exists as a mineral asset that can be more productively used beyond its conventional applications as a combustion fuel or in the production of steel. An internal survey identified more than a dozen pathways to markets for coal-derived products that belie the notion that coal's only useful purposes are for steam and electric power generation or for producing coke for steelmaking and other metallurgical applications. These results are as compelling as they are complex. The market landscape is an evolving mosaic of products, covering everything from undifferentiated commodities to advanced nano-carbon structured specialties, ranging from multi-billion-dollar liquefaction fuel assets to novel single-use hand-held biosensors.

To grapple with the strategic perspectives and with the main objective of developing a coherent outlook, a systematic approach for characterizing and prioritizing opportunities was chosen as a means of mapping out “directional opportunities.” The chosen tool was the GE-McKinsey nine-block framework^v. The approach recognizes the complexities of comparing a diverse portfolio of business units – in this case a diverse set of product opportunities – and resolves the challenges of putting everything on the same basis by considering two common features; namely, *market attractiveness* and *competitive strength*.

Market attractiveness was quantified based on the current size of the targeted market, forecasted growth rates of the overall market and market pull factors. Competitive strength was quantified based on current coal-derived market share, coal's competitiveness versus incumbents and individual product strength attributes, including perceived technical viability, perceived commercial viability, U.S. strategic implications, environmental impact and future potential growth opportunities. This exercise was intended to be directional in terms of identifying clusters and commonality among them. The results showed groupings of product classes essentially along three main themes: Traditional, Core and Performance.

TRADITIONAL – This group is characterized by high commodity volumes, is technically and technologically proven, requires high capital expenditures and provides only marginal economic opportunity in the U.S. as oil and gas currently out-compete coal in the U.S. This group would benefit from improvements in conversion efficiency, hybridization with natural gas co-feed synergies and deployments at smaller modular scale. NCC recommends further and continued techno-economic assessment of this area of opportunity.

CORE – This group is characterized by moderate industrial-scale volumes, is technically proven, requires only moderate capital expenditures and provides a sizeable opportunity in the U.S. It would benefit both from process efficiency gains to reduce production costs and from new investments in product application research to serve growing needs for more advanced products in the specialty sectors currently being served. NCC recommends more investment in product application R&D and in new systems and processes for manufacturing. This group needs to grow.

PERFORMANCE – This group offers specialty volumes of high-performance materials that utilize the inherent and unique chemistry advantages embedded in coal, which cannot easily be replicated by other generic carbon sources. Many products in this cluster can out-compete petroleum- and natural gas-derived surrogates. These products enable a new economy for lightweight, high-strength, energy-saving, electrically- and thermally-conductive materials. The optimistic outlook for this product class is one of rapid commercialization from small-scale modular facilities to larger industrial facilities with production volumes and economics of scale that reduce costs, driven by the ultimate ability to supply commodity volumes of coal-derived materials that meet or exceed the cost and performance of existing materials to established and new markets in the construction, automotive, electronics and environmental sectors. This group offers innovation and disruption opportunities, unique chances to shape the future, high upside potential for large-volume consumption premised on price elasticity of demand and the potential ease of substitution with low-cost coal-derived materials in large commodity sectors such as steel, aluminum, cement, asphalt and building products. NCC recommends additional research, development, investment and encouragement of commercialization opportunities in this group.

The compass for growth opportunities is now being set, and it is imperative that stakeholders consider implications associated with each of the three broadly-classed opportunities.

Market Attractiveness and Product Strength Assessments

The leading coal-to-products technology/market pathways were identified by researching the historical conventional uses of coal, summarizing known pathways in operation currently, and envisioning a future characterized by both modest commercialization of new coal-derived products and re-commercialization of some existing coal-based processes.

One of the first coal-to-product processes brought kerosene to the market more than 150 years ago. Since that time, coal has been utilized and considered in a variety of non-conventional uses. These range from the steel and cement sectors, to use in early synthetic dye manufacturing, to large-scale liquefaction and chemicals manufacturing. Indeed, overseas countries, especially China, are using coal today for such purposes in volumes approaching 50% of the U.S. consumption of coal for power generation. See Table 2.1 for volumes of coal utilized.

		Coal Consumed	Yield to Liq. products ^[vi]	Coal Products
		million TPY	%	million TPY
Indirect Coal Liquefaction	Gasification Fuels and Chemicals ^{[vii], [viii], [ix]}	270	40%	108
Direct Coal Liquefaction	DCL Fuels and Chemicals ^{[x], [xi]}	2	55%	1
	DCL Fuels and Chemicals ^{[xii], [xiii], [xiv]} via Low -Temp Pyrolysis Route	28	14%	4
Coking of Metallurgical Coal	Coal Tar Pitch ^[x] as precursor liquids for Carbon Black, Electrodes and Chemicals		4%	16

Table 2.1 General Estimates for Non-Conventional Usage of Coal

As a point of reference, the Energy Information Administration (EIA) reported 2018 U.S. coal production at 755 million tons^{xv}. Rough estimates from Nexant indicated that 300-400 million tons/year of coal is consumed globally for non-conventional uses. This estimate does not include coal consumed for metallurgical coke making, nor does it include the coal consumed in calcining of cement. Of the 300-400 million ton/year estimate, roughly 95% of that amount is used in China, and 95% of the China total is for gasification-based production of liquid fuels and chemicals.

These estimates are based on non-proprietary information available from public sources. They are presented here to show the general coal consumption structure, for comparison purposes, as a qualitative indication of relative size, and have not been independently verified or peer reviewed in terms of their accuracy.

An additional view is presented in Table 2.2 to show the existing worldwide market for carbon products, which includes the production of activated carbon, carbon black, carbon fiber, synthetic graphite and carbon electrodes among others; some but not all of these carbon products are made from coal currently. The worldwide annual sales volumes shown represent the amounts of the carbon products sold globally.

Many of these products are heavily reliant on two key feedstock sources; namely coal tar pitch and petroleum pitch, and to lesser extent mined graphite. However, both petroleum-based pitch feedstocks and coal-based pitch feedstocks have declined in the U.S. Petroleum-based pitches have declined due to lighter refinery feeds and higher levels of contamination. Coal tar pitches have declined as a result of new less coke-intensive steelmaking processes and off-shoring. Nonetheless, the markets for the carbon products listed have continued to grow, and, as necessary, together with the requisite process technology development work, coal-based pitch can be used to replace petroleum-based pitch as a feedstock.

Recent higher technology innovations involve coal used in the development of high-value nanomaterials, in advanced carbon materials in the med-tech sector and in battery storage applications. Other emerging technologies are seeking to develop coal core composites for roofing, coal plastic composites for decking and carbon foams for use in building material and structural applications. These processes are characterized by a minimal number of processing steps and high-volume infrastructure application opportunities. The novel extraction of rare earth elements (REEs) from coal, and the use of modified lignite coal for agricultural soil amendment purposes, are also in the development and commercialization stage.

Product	Primary Feedstocks	Main Applications	Y2011^{xvi} Worldwide Sales, tons	Y2018^{xvii} Worldwide Sales, tons
Activated Carbon	Coal Biomass, other	Sorbents, air and water purification	na	1,380,000
Binder Pitch	Coal Tar Pitch Petroleum Pitch	Anodes (Al Smelting) Arc Furnace Electrodes (steelmaking)	1,500,000	5,500,000
Impregnation Pitch	Petroleum Pitch Coal Tar Pitch	Electrodes, Composites	380,000	
Mesophase Pitch	Petroleum Pitch Coal Tar Pitch	High Performance Composites, Fibers	3,700	
Anode Coke Uncalcined Calcined	Petroleum Resid	Anodes (Al Smelting)	8,000,000 6,200,000	26,000,000
Needle Coke	Petroleum Pitch (US) PP + CTP (Japan)	Arc Furnace Electrodes (steelmaking)	1,300,000	1,000,000
		EV Batteries	na	600,000
Graphite	Natural Graphite	Electrodes, others	na	1,200,000
Carbon Fiber (PAN)	Petrochemicals	Non-graphitic composites	24,000	78,500
Pitch Fibers	Coal Tar Pitch Petroleum Pitch	Graphitic composites	3000	4,000
Calcium Carbide	Coal derived coke	Acetylene, PVC, BDO, VAM	na	30,000,000
Carbon Black	Petroleum Pitch, Coal Tar Pitch	Rubber additives, various other	8,000,000	16,000,000
Carbon Foam	Petrochemicals, Coal, Coal Tar Pitch	Structures, Electrochem. Systems	200	151
Coal Soil Amendment	Lignite Coal	Soil Nutrient, Fertilizer, Remediation	na	1,000
TOTAL			25,410,900	81,763,651

Table 2.2 General Estimates of Existing Worldwide Markets for Carbon Products

The schematic representation shown in Figure 2.1 is a simplified depiction meant to cover the main production pathways and markets under consideration. These are not meant to be exhaustive. While more than a dozen coal process technology/market pathways are addressed in this report, a number of processing pathways were not considered to be within the scope of the report; e.g., the conversion of coal-derived CO₂ to products is not covered.

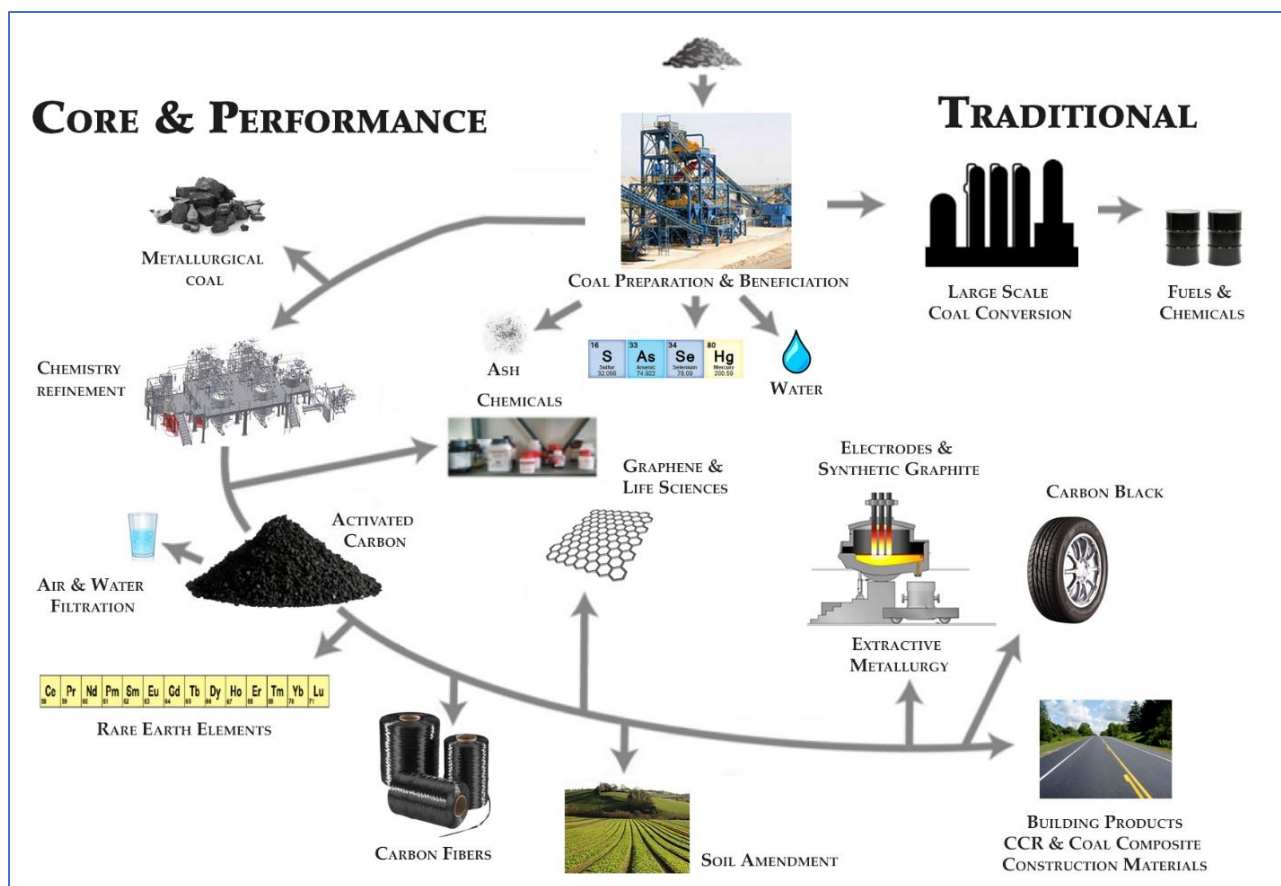


Figure 2.1 Non-Conventional Uses of Coal:
CORE & PERFORMANCE routes (left and lower) and **TRADITIONAL** routes (upper right)

In conducting this report, NCC first gathered key attributes for each of the major coal process technology/market pathways, and then characterized these with respect to product competitiveness and market attractiveness/viability.

It should be noted that the published literature is incomplete when it comes to emerging coal-to-products technologies, particularly with respect to economics and quantitative performance attributes. Some techno-economic studies have been concluded for coal conversion processes, and these were used as references where available. However, these studies were relatively narrow in scope given the wide spectrum of potential alternative applications for coal. Therefore, detailed references are not available for all the technologies covered in this report, and as such this remains an area that could benefit from more detailed analysis by the DOE and other organizations. Until that can be accomplished, a certain amount of extrapolation is needed to execute and evaluate the qualitative rankings versus purely quantitative comparisons.

The results of the GE-McKinsey nine-block analysis are graphically represented in Figure 2.2 and detailed below. In the graphic, each data point consists of two concentric bubbles. The size of the darker blue inner bubble is a qualitative representation of the total size of the market (in annual revenues) that coal is able to address; the size of the lighter blue outer bubble is a qualitative representation of potential market growth over the next 25 years. The addressable markets are defined as those which according to precedent may be served by coal, where in many cases, however, are primarily served by oil and gas, depending on prevailing market dynamics and relative competitiveness among these feedstocks.

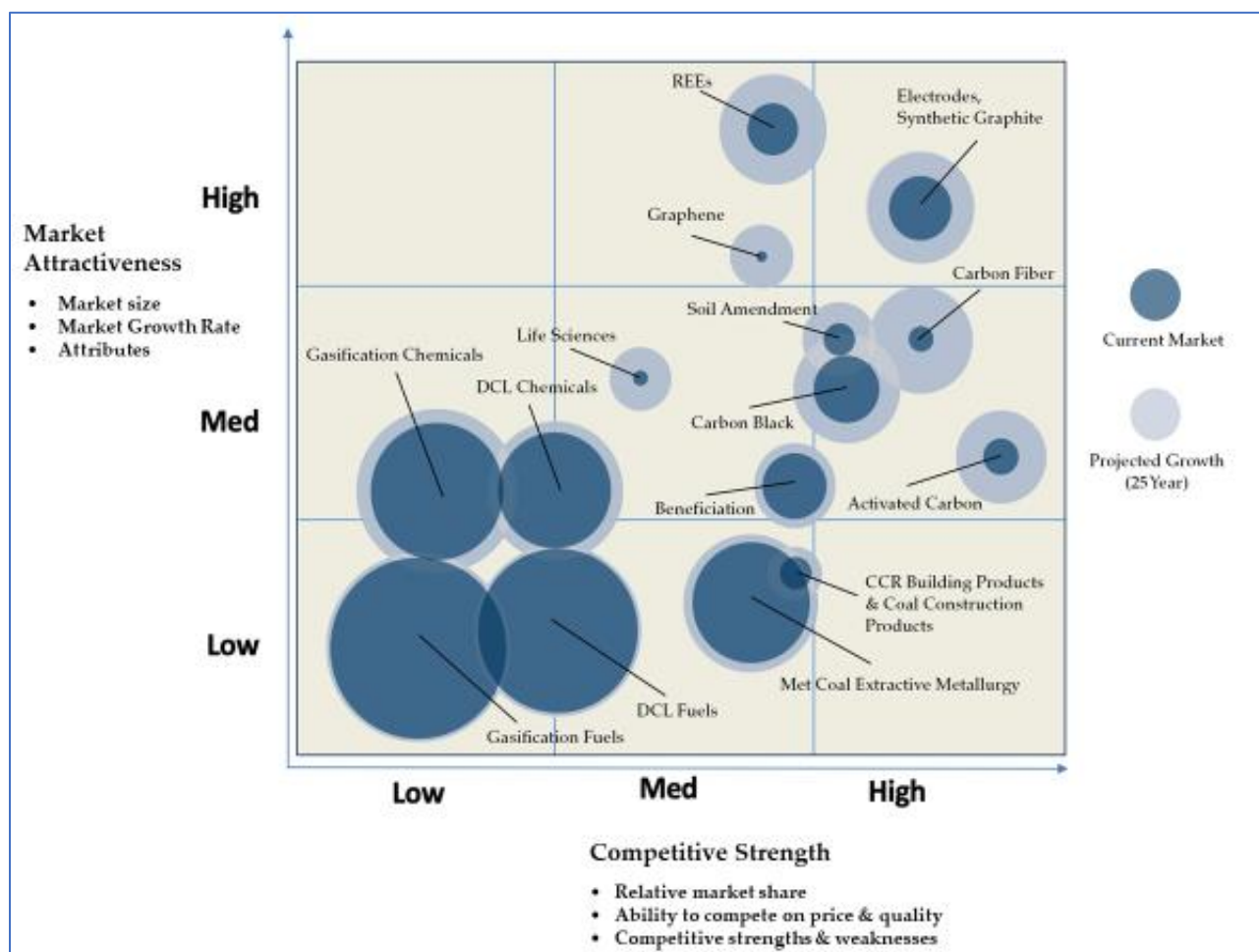


Figure 2.2 A Nine-Block Depiction of the Main Coal-to-Products Technology-Market Pathways

It should be noted that the results of the GE-McKinsey nine-block analysis are not intended to serve as a substitute for business planning purposes. To be sure, there are a multitude of attractive opportunities that this simple process does not capture well, especially those associated with the newest emerging technologies which have not yet established a sizeable market presence and, in some cases, have not yet established the new markets that they will create. For example, new coal carbon-based building materials could emerge in the future in ways that are not reflected in today's assessment.

TRADITIONAL - Coal commodity products, including bulk chemicals and fuels, qualitatively fall in to the Low Market Attractiveness - Low Competitive Strength classifications.

- **Gasification-based Liquid Fuels and Chemicals** - Although technically feasible, and widely practiced in China, the feedback gathered from this report did not indicate that these products from coal have the economic potential to compete with natural gas and petroleum-based fuels in the near to mid-term in the U.S. This is due in large part to the success of the U.S. oil and gas industry in driving down petroleum and natural gas feedstock costs through technological advances such as hydraulic fracturing. It is also due to the significant capital costs required to build the multi-billion dollar coal-based facilities that can produce products at the economies of scale needed to compete with the already-competitive oil and natural gas refining industries. If petroleum or natural gas costs were to significantly increase in the future, then coal could potentially become a competing source of these products. Larger market potential for these coal-based products could also be possible if new lower-cost processes significantly drove down processing and conversion costs.
- **Direct Coal Liquefaction-based Fuels and Chemicals** – Although direct coal liquefaction (DCL) is technically feasible, it is not widely practiced. Overall production costs, especially those associated with hydrogen consumption, are lowered with use of low-cost natural gas co-feed to produce fuels and aromatic chemicals. The information gathered for this report indicate that this technology approach is more competitive than indirect coal liquefaction (ICL). However, the NCC report did not undertake a detailed comparison with leading competition from petroleum-derived fuels and aromatic chemicals.

CORE – The specialized products identified below qualitatively fall into the Medium Market Attractiveness - High Competitive Strength classifications.

- **Metallurgical Coal and Coke (for extractive metallurgy uses)** – This is an established processing technology, mainly serving the steelmaking industry and lower-volume non-ferrous metal smelting processes. Overseas markets are growing in comparison to U.S.-based operations, which face competition with imported steel products. No major upturn in the domestic demand for the combined consumption of metallurgical coke and direct use of coal extractive metallurgy is foreseen during the periods of interest to this study. Though a relatively small co-product of coke-making, coal tar pitch has risen in demand and shortened in supply in recent years as a precursor for specialized carbon-based product applications.
- **Coal Beneficiation** – This is a well-established and important intermediate processing step that enables products rather than being a product itself. Traditionally, this includes the first processing step for raw coal, including sizing and physical removal of unwanted non-carbon bearing mineral (rock). Increasingly sophisticated new advances now target significant reductions of unwanted moisture, trace elements, and sulfur and enable the ability to purify very fine coals including, for example, the cleanup of coal from tailing ponds. Coal beneficiation holds the promise of providing higher-quality coal feedstocks to the increasingly higher-purity demands across all coal consumption sectors.

- **Activated Carbon** – This product derives from established processing routes using coal and biomass feedstocks, mainly serving the specialty sorbent market for water purification and air purification demands, which are growing at or above global GDP rates. New specialized uses include areas such as low-cost industrial gas separations, CO₂ removal from mixed gases and other energy-saving applications that could spur future demand.
- **Carbon Black** – Established processing routes from coal and petroleum residues are used to produce this product which mainly serves the tire industry as a toughening additive to automotive rubber. China has built its carbon black industry on coal-derived co-products (from coking) while the rest of the world continues to use petroleum residues as feedstock. The opportunity for substitution requires further assessment.
- **Coal Combustion Residuals (CCRs) and Coal to Building Products** – There is an established processing route for converting fly ash into value-added construction products, cement additives and other novel uses. It is price-competitive versus on-purpose production of substitutes, i.e., from energy-intensive calcining routes. New emerging technologies are also seeking to develop direct coal core composites and direct coal plastic composites for use in building material and structural applications. Market demand and attractiveness could potentially surge, especially if the promise of low-cost coal-sourced materials meet high performance demands in these new and potentially high-volume applications.

PERFORMANCE – This sector includes engineered advanced products and rare earth elements, which qualitatively fall into the High Market Attractiveness - High Competitive Strength characterization.

Coal has a variety of specialized uses, most of them currently low-volume applications but growing at rates significantly exceeding global GDP. Many of these depend on coal tar pitch and its inherent carbon chemistry to be fully formed into advanced carbon materials which can outperform other known alternatives from petroleum, biomass and natural gas derivatives. Much of the past R&D on these niche applications has taken place, and continues to take place, in U.S. national labs and established U.S. research centers for specialized aerospace and defense applications.

At the present time, new domestic markets are being catalyzed by greater market demands for high-performance advanced carbon materials in high-performance applications requiring, in some cases, ultra-light-weight, ultra-high-strength and high electrical- or thermal-conducting materials. High-performance products are enabling a new economy that is being built in areas such as the automotive sector, with trends toward higher capacity, lighter weight electric vehicle (EV) batteries, high-pressure fuel storage tanks and lighter weight body panels as several examples.

- **Carbon Fiber** – First developed in the 1960s for demanding applications as a space age material for satellites and military aircraft, carbon fiber is now finding its way into the infrastructure, energy and transportation sectors. A burgeoning new role is in reducing the use of energy-intensive materials such as steel and concrete. It is widely used in Japan for seismic strengthening and repair of concrete structures, and holds promise as a potential component in asphalt, lumber composites and even roofing materials. Market demand could potentially surge, especially in the automotive and aviation sectors, if the promise of low-cost coal-sourced precursor materials come to fruition.
- **Synthetic Graphites and Electrodes** – This is another strategic material, first developed to serve the needs of two core industries: aluminum smelting (anodes and cathodes) and electric arc furnace (EAF) steelmaking (electrodes). These products are now finding their way into Li-ion battery applications and as conductive pastes in electronic applications. Market demand is poised to surge if the promise of low-cost coal-sourced materials begins to outcompete natural graphite at disruptive production costs.
- **Graphene and Graphene Oxide** – Recently discovered atomic-layered carbon, found in coal, holds promise as a “wonder material” exhibiting the highest known material strength ever recorded. As a lab fascination it is already getting traction in performance markets and will find its way into new applications that have not been fully envisioned at present. Some of these applications include uses such as a toughening agent in building materials and as an electrical conductivity enhancer in new metal alloy systems. Both hold promise in terms of efficiency gains. These products are worthy of additional study and application research.
- **Rare Earth Elements (REEs)** – Produced extensively and almost exclusively in China from enriched ore deposits, rare earth elements are not “rare” but of high strategic value. Single-source basis (China) has led to market availability concerns worldwide. Research efforts now point toward residual coal ash and mining residues as potentially abundant and low-cost feedstocks. A proportion of coal deposits are naturally rich in REEs, which are essential for the construction of an array of products such as batteries and electromagnetic motors, and most importantly numerous defense applications. The extraction of REEs from raw coal or coal by-products (tailings, ash and aqueous effluent) holds significant promise as an important method to secure the industrial supply of critical elements. A number of different groups are pursuing various technical paths that will result in viable options for commercial domestic production of REE oxides.
- **Soil Amendment (Humic Acid and Humate)** – Lignite coal has a long history of use as a fertilizer; it is currently being assessed as a large-scale solution to help counter the problem of desertification with remediation. If upgraded lignite coal performs as an effective agricultural additive, then this could be a significant alternate high-volume use of a valuable coal resource. Lignite contains natural organic compounds known as humate, which are from the decomposition of plants and are found in soil and peat, as well as lignite. Application of humates to soils is beneficial, promoting increased water retention, growth of beneficial micro-organisms, root growth and plant yield serving as a source of natural nutrients and replacement of lost top soil. Humate and humic acid products could play an important role in counteracting the deterioration of fertile land, a challenge caused by intensive farming, erosion and drought.

- **Life Science (Biosensors)** – Specialty carbon materials are used in prosthetics and implants and as carriers in drug delivery. In another example, graphene is very suitable for use in sensor technologies. Moreover, like all life forms it is carbon based, making it an ideal platform for biological applications. In the past several years, novel sensing platforms have been proposed with graphene. Several of these platforms were used to immobilize biomolecules, such as antibodies, DNA and enzymes to create highly sensitive and selective biosensors. These coal-based biosensors can be particularly useful in life sciences and medicine, since biosensors with high sensitivity and specificity can significantly enhance patient care, early diagnosis of diseases and pathogen detection in clinical practice.

Although the quantities of coal consumed may initially be relatively small, the value uplift and rate of growth for the Performance product category is forecast to be the highest. A recent study by McKinsey^{xviii} shows that by 2030, the use of lightweight materials in automotive production will approach the levels currently used in aviation. As an essential light weighting component, carbon fiber will experience two decades of strong growth, with carbon fiber growing at a CAGR rate of almost 20% – an impressive number though starting from a low base. This number could increase dramatically if certain conditions occur, such as greater CO₂ reduction pressure or further cost decreases of carbon fiber.

Based on carbon product data presented in Table 2.2, a combined total of about 50 million tons of carbon black and carbon anodes are produced globally from coal pitch and petroleum pitch. If all 50 million tons of products were made from coal tar pitch, assuming a 25% yield of carbon products from coal, then this would represent 200 million tons per year of coal consumption based on existing addressable markets. As a point of reference, EIA reported U.S. coal production at 755 million tons in 2018.^{xix}

It is often difficult to project the size of rapidly growing markets that benefit not only from organic growth but from price drops that result from increased volumes. In the past, all “expert” market forecasts for silicon chips, photo-voltaic cells and lithium-ion batteries were proven to be woefully conservative. Moreover, the market, job creation and overall infrastructure impact may ultimately outsize initial estimates resulting in greater long-term economic benefits for coal communities.

Chapter 3. Recommendations

To realize the opportunities for using domestic coals to produce coal-to-products (e.g., solid carbon products, chemicals, fuels, and rare earth elements) will require a coordinated national commitment. Making such a commitment will benefit the U.S. economy and environment, our nation's trade balance, domestic manufacturing of both defense and non-defense products, and, in particular, mining and manufacturing jobs in critical coal-producing states. The following strategic objectives and action items are recommended for consideration and implementation by the U.S. Department of Energy.

Strategic Objectives

The National Coal Council has reviewed the supply chains for manufacturing products from coal in the U.S. and is recommending that the U.S. become a competitive producer and supplier of coal-derived carbon products, rare earth elements (REEs) and select chemicals and fuels. Accomplishing this objective will require significant investment and development, both at the governmental and strategic industrial levels. It will also require productivity and efficiency improvements in infrastructure and process technologies throughout the coal-to-products supply chain in order to successfully commercialize these opportunities.

The NCC recommends three primary strategic objectives be pursued by the U.S. Department of Energy to ramp up U.S. manufacture of coal-derived solid carbon products, chemicals, fuels, and REEs.

Establish a focused R&D program on coal-to-products.

Additional research and development (R&D) is needed to achieve commercially viable technical performance-to-cost ratios for the manufacture of coal-derived solid carbon products, chemicals, fuels, and REEs in the U.S.

Accelerate research-to-commercial deployment in coal-to-products market sectors.

Competing successfully in a global economy requires that the U.S. bring new technologies and related manufacturing to market much faster via replicable modular systems. To avoid being out-paced by other countries, gaps in funding and delays in progression from research to commercial deployment, including new-skills workforce development, must be eliminated.

Incentivize private sector investment in coal-to-products production and manufacturing sectors.

Efficient use of public and private sector financial capital requires alignment of private sector interests and investment readiness with government public sector R&D and economic development investment plans, as well as with defense procurement schedules. Steps must be taken to establish a stronger private sector investment appetite for first-of-a-kind (FOAK) and subsequent single-digit coal conversion plants and end-product factories, in order to quickly move DOE supported coal-to-products technologies into commercial operation, to create jobs and to improve U.S. balance of trade.

Tactics

Specific tactics and action items recommended to achieve these strategic objectives are detailed below and specify **WHAT** must be done and **WHY**.

A. Strategic Objective: Establish a focused R&D program on coal-to-products.

- Establish a national R&D program for advanced carbon products and manufacturing within the U.S. Department of Energy.
A committed R&D effort to advance coal-to-products technologies would enhance prospects for commercialization in an efficient and timely manner. It is recommended that screening tools are established so that R&D investments can be directed toward those technologies that are most likely to commercially succeed and have a positive impact.
- Sustain a multi-decade base level of Federal commitment and support.
From a historical perspective, Federal support for coal upgrading and coal conversion technologies has tended to be cyclical, with various crises or economic or national security concerns serving as primary drivers. Such cyclical support can lead to losses of critical expertise and program momentum during periods of reduced support. It is recommended that an adequate base level of Federal support be continuously maintained so that critical needs can be addressed more rapidly and more effectively as they arise.
- Implement a broad-based interagency coordinated program to accelerate coal to fuels and products development.
Similar to the Biomass Research and Development (BR&D) Board^{px} created through enactment of the Biomass Research and Development Act of 2000, bring together in a formal intergovernmental team the required agencies and departments to work concurrently on positioning all the necessary elements for success, including U.S. Export Administration Regulations (EAR) and International Traffic in Arms (ITAR) compliance.
- Elevate the priority of and increase R&D funding for coal-to-products technologies.
Establish a national commitment to develop and deploy U.S. coal-to-products conversion technologies and U.S. manufacturing capabilities to revitalize the coal industry and communities. Such a commitment goes beyond typical Department support for energy plant development and scale up and adds Department support for development and deployment of new manufacturing methods and processes to achieve robust economic and job growth from manufacture of carbon products derived from coal. The DOE Office of Fossil Energy can leverage existing programs within the National Institute of Standards and Technology (NIST), the Department of Defense (DOD) and the Department's own Advanced Manufacturing Office (AMO) to jump start and place coal-to-products on a fast-track program.

B. Strategic Objective: Accelerate research-to-commercial deployment in coal-to-products market sectors.

- An Office of Carbon Products within the U.S. Department of Energy would establish the required national commitment and empower DOE program managers to pursue the strategic objectives and achieve the desired economic growth, job creation (such as the American Jobs Project's report entitled, The Wyoming Jobs Project: A Guide to Creating Jobs in Carbon Tech^{xxi}) and national security benefits. The Office of Carbon Products would be tasked with building one or more Carbon Advanced Material, Manufacturing and Production (CAMP) centers at coal mining sites in key coal states to accelerate the pace of research-to-commercial deployment of coal-to-products and to develop repeatable modular plant designs.

Past designs for commercial facilities have focused on extremely large plants for converting a solid (coal) to a gas (chemicals) or liquids (fuels). Although technically successful, the U.S. benefits from very low cost and plentiful carbon liquids (crude oil) and carbon gases (syngas, natural gas). Since the 1950s almost all of its carbon solids (coal) have been burned. With the advent of carbon-based advanced materials, the time has now come to focus on direct coal to solid carbon product processing facilities and to do so with a focus on advanced manufacturing. One or more CAMP centers need to be built to spearhead the effort and to bring together America's best and brightest to achieve this important national objective.

- Support multiple first-of-a-kind projects throughout the U.S.
The U.S. is blessed with a diversity of coal compositions that are geographical distributed throughout the country. Each coal resource provides different commercial strengths and weaknesses and different technical challenges for successful operation that need to be understood in order to be successfully leveraged. Geographical distribution of industries critical to defense applications provides greater survivability of critical economic and defense industry assets against adversary attacks. Lessons learned from the Nth-of-a-Kind version of each technology will reduce the cost of deployment and provide an economic advantage for U.S. manufacturers.
- Expand DOE Loan Guarantee Program.
Review the eligibility criteria for the existing DOE Loan Guarantee Program and affect changes needed to allow loan support for coal-to-products conversion plants and factory opportunities.
- Dramatically reduce DOE Loan Guarantee Program costs, red tape and processing time.
Uncertainty and risk associated with the DOE Loan Guarantee Program approval process time and possible delays elevates private sector investor risk assessments such that opportunities are not selected for investment.

- Apply U.S. Department of Defense Manufacturing Readiness Levels to DOE programs.
The DOD developed manufacturing readiness levels (MRLs) to provide better coordination between technology development efforts and U.S. capability to affordably manufacture new technologies. Likewise, the DOE can apply MRLs to improve coordination between science and technology development and alignment with U.S. manufacturing method and process development. DOE can also use MRLs as a program and project progress and management evaluation tool.
- Target defense applications and national critical materials to avoid “Valley of Death” stall-out.
Many of the products highlighted in this report have substantial defense applications that are quality early-adopter premium market opportunities that can support private sector investment justification for first-of-a-kind (FOAK) coal conversion plants and end-product factories. Coordination with the DOD should be pursued to jointly identify and prioritize the chemicals, fuels, materials and products most desired by the DOD and to align DOE R&D program timelines.
- Target dual-use applications to quickly grow markets and demand for coal.
Review DOD dual-use programs to quickly grow total market demand for coal-derived solid carbon materials, chemicals, fuels and REEs.
- Ensure U.S. developed technologies are deployed in the U.S.
Unfortunately, many of the new uses and applications of coal and coal products technologies are now being exploited in China but are based upon technology originally developed in the U.S. and other countries. These new uses and applications of coal technology have not been replicated here in the U.S. due to historically restrictive environmental and regulatory issues and the availability of low cost and plentiful oil and natural gas resources. However, there are high-value wealth and job creation opportunities available here in the U.S. in which coal has a material advantage over oil and natural gas.
- Address U.S. Export Administration Regulations (EAR) and International Traffic in Arms Regulations (ITAR).
Many of the advanced carbon materials identified in this report require EAR and ITAR compliance that inhibit academic institution participation in recommended R&D programs when projects do not fall under the basic research exclusion.

C. Strategic Objective: Incentivize private sector investment in coal-to-products production and manufacturing sectors.

- Establish public-private partnerships.
Facilitate early engagement and commitments to ensure the necessary entrepreneurial and investment communities buy in and are prepared to lead manufacturing and commercialization of technologies advanced by the Department to convert coal into solid carbon materials, chemicals, fuels and REEs. All government departments and agencies must work together with the private sector in a tightly coordinated manner to achieve maximum economic value, job creation, trade deficit reduction and national security benefits.
- Provide tax and other investment incentives and subsidies to facilitate the rapid development and commercialization of coal-to-carbon products.
In previous National Coal Council reports^{xxii}, the success of tax and policy incentives in facilitating the rapid growth and commercialization of renewable energy technologies has been documented. There is a precedent for the use of these measures to advance technology commercialization.
- Validate revenue and business models and management strategies in addition to technology performance and cost.
Revenue and business models, as well as management strategies can be more critical to commercial success than just validation of technology performance and cost. It is essential that the Department incorporate development and validation of credible revenue/business models and management strategies concurrent with technology development activities.
- Expedite environmental and permit approvals.
Delays and cost overruns associated with the National Environmental Policy Act (NEPA) reviews can add several years to commercialization of DOE-supported technologies and hence delay job creation and national security benefits. Pre-approved project templates could be developed by DOE and tailored for individual projects to provide faster NEPA review cycle time at less expense.
- Analyze the condition and suitability of existing infrastructure assets.
Reliable, efficient and affordable infrastructure is essential to grow sustainable coal to carbon solid products, chemicals, fuels and REEs economic sectors. Infrastructure repairs, upgrades and improvements will likely be required for successful U.S. competitiveness and job creation in the global economy.
- Use shuttered and producing mines, coal power plants and coal communities as economic revitalization zones for new coal to fuels and products production and manufacturing centers.
Brownfield coal mines, power plants and communities with existing infrastructure assets offer low startup costs to establish coal to chemicals, fuels, REEs and carbon products.

- Update regulations, legislation and permitting.
Commercial deployment of the many new technologies and manufacturing capabilities envisioned in this report are at risk of being delayed due to lack of inclusion within existing laws, regulations and permitting requirements. Given that changes to existing laws, regulations and permitting requirements are generally a multi-year endeavor, it is recommended that the Department immediately identify and begin work to resolve gaps and barriers within existing laws, regulations and permitting requirements three to five years in advance of filing first plant and factory permit applications.
- Provide DOE financial support for pre-FEED and FEED projects.
Preliminary front end engineering and design (pre-FEED) and FEED assessments can facilitate financing and development of commercial coal-to-products facilities. DOE support for FEED initiatives can strengthen and accelerate commercialization.

Chapter 4. Overseas Coal-to-Products Markets and Outlook

Key Findings

- Nations worldwide are using coal in a variety of non-combustion applications, including production of chemicals, carbon products, transportation fuels, critical minerals and high-quality beneficiated coal.
- Development of technologies and markets for coal-based products can create new markets for U.S. coal exports, expanded employment opportunities in the U.S., and potential for improvements in the U.S. balance of trade.
- An examination of research and development (R&D) activities for non-conventional coal-based technologies in overseas markets may aid identification for similar U.S. R&D and commercialization pursuits to expand domestic markets for U.S. coal products.

Overview

Coal has seen a multitude of uses worldwide that may be considered as non-conventional applications, here defined as those outside of power generation and steelmaking markets. Although coal has historically been used in the U.S. as a feedstock for various non-conventional applications, other feedstocks, such as petroleum and natural gas-derived products, have more recently been substituted. In international markets, however, these alternative feedstocks are often less available and more costly.

In many countries, this has led to the use of coal as a feedstock for numerous non-combustion production processes. This provides export potential for U.S. coal and coal-derived products. Additionally, coal use outside the U.S. for these applications, has led to continued new overseas R&D associated with coal-based production processes. An examination of this international research work, especially where it has led to commercial facilities, may lead to the identification of opportunities for similar deployments in the U.S. to expand both domestic and export markets for U.S. coal products.

Some current markets for coal have the potential for expansion through the type of R&D activities that produce both commercial improvements and next generation (NextGen) technologies. Among these are coal-to-liquids (CTL), fuels and coal-to-chemicals (CTC) applications, and selected materials that are currently derived to some extent from coal, such as synthetic graphite products and carbon fibers (CF).

The development of new and NextGen technologies for coal-based products can create new markets for U.S. coal producers. Examples include the production of graphenes from coal and extracting critical mineral (CM) commodities, such as rare earth elements (REEs) from coal byproducts and over/under burden.

The following is a summary examination of uses for coal outside the U.S., in key areas such as the production of CTLs, transportation fuels and chemicals, carbon products, REEs and the metallurgical sectors. A discussion of coal beneficiation with respect to these markets is also presented.

In addition to expanding the market potential for U.S. coal products, R&D within these market sectors can also lead to expanded employment opportunities within the U.S., as well as the potential to improve the U.S. balance of trade (reductions in import requirements and trade deficits).

Coal Conversion

Coal to Liquids, Fuels, Natural Gas, and Chemicals

The use of coal-derived syngas for fuels production, known as indirect coal liquefaction (ICL), dates back to the discoveries associated with the Fischer-Tropsch (FT) process in the 1920s. Developments in Germany were the subject of extensive investigation by the U.S. Bureau of Mines following World War II.^{xxiii}

Sasol (South African Synthetic Oil Liquids) was formed by the South African government in 1950, with a charter to develop the capability to produce liquid fuels from South African coal reserves. In 1955, the Sasol-I plant was constructed in Sasolburg to demonstrate the technology to produce liquid fuels from coal via gasification and FT synthesis. Sasol subsequently undertook a massive program to build two large ICL facilities, Sasol II and III in Secunda. These facilities started operations in 1980 and today produce 160,000 barrels per day (BPD) of liquid fuels from about 40 million metric tons per year (MMTPY) of coal.^{xxiv}

In China, R&D activities into the FT process have led to several commercial ICL projects using the FT technologies developed by Synfuels China Technology Co. Ltd. These include plants in stages ranging from development to operational, such as the Yitai Dalu and Guizhou Projects (50,000 BPD each), the Yitai HJQ Project (25,000 BPD), the Luan Project (25,000 BPD) and the Shenhua Ningxia Project (100,000 BPD).^{xxv}

The combined aggregate production capacity of the referenced plants in China and South Africa is over 410,000 BPD. By comparison, U.S. crude oil refining capacity in January 2017 was more than 45 times larger at 18.6 million BPD.^{xxvi}

Among the other products that can be produced from syngas is synthetic natural gas (SNG). In India, a large coal gasification project is being undertaken by Reliance Industries, Limited, which will produce multiple products from syngas, including SNG and hydrogen.^{xxvii} The plant is designed to use approximately 29,000 metric tons per day (MTPD) of petroleum coke as feedstock, with the flexibility to accommodate 35% coal as feedstock^{xxviii}. As such, in addition to pioneering polygeneration of SNG with other products, the facility has the potential to use significant amounts of coal.

In addition to synthetic fuels, the conversion of coal-derived syngas to chemicals is a significant practice overseas. Both methanol and ammonia are produced from coal, as products themselves or as intermediates used in turn to produce fuels and olefins, in the case of methanol, and fertilizers and urea, in the case of ammonia.

Methanol Production from Coal

As of 2017, coal accounted for 85% of the feedstock for methanol production in China.^{xxix} Three years earlier, China accounted for over half of both world methanol production and consumption.

In 1985, a plant was commissioned in New Zealand, using the then Mobil (now ExxonMobil) methanol-to-gasoline (MTG) process, with a capacity of 14,500 BPD.^{xxx} This technology has also been adopted in China, with a 2,500 BPD, coal-based MTG plant entering service in 2009. In China, numerous operating plants for the production of olefins and polypropylene from coal-derived methanol were reported in 2013, with more under development.^{xxxi} In 2017, the Jiangsu Sailboat Petrochemical Co. Ltd. started up a methanol-to-olefins (MTO) plant with a production capacity of 833,000 MMTPY. A technology vendor for the project (UOP) forecast at the time (2017) that China would be investing \$100 billion in CTC technology over the next five years.^{xxxii}

Coal to Fertilizer

China, India, and the U.S. are, in that order, the largest consumers worldwide of nitrogen fertilizers.^{xxxiii} By 2016, China had become both the largest producer and exporter of nitrogen and phosphate fertilizer products.^{xxxiv} In 2014, 86% of Chinese ammonia production capacity was based on coal,^{xxxv} and, according to China's 13th Five Year Plan, by 2020, 81% of China's urea production capacity was forecast to be coal-based.

An example of a recently constructed urea production facility based on coal gasification is the China XLX Fertilizer's Plant V in Xinjiang Province, which started up in 2015. This plant has a 520,000 MTPY production capacity.^{xxxvi}

Coal-based fertilizer production in India is a decades-old practice.^{xxxvii} An example of a newer project is the development of a coal gasification-based fertilizer plant by Talcher Fertilizers, Limited, at the site of an older gasification-based fertilizer plant that closed in 2002. The projected production rate for this project is 1.27 MMTPY. Feedstock is to be high ash content Indian coal, with the provision to also use up to 25% petroleum coke in the plant feed.^{xxxviii}

Direct Coal Liquefaction

Direct coal conversion processes convert coal into liquids by directly breaking down the organic structure of coal. Since liquid hydrocarbons have a significantly higher hydrogen-carbon molar ratio compared to coal, DCL technologies use hydrogenation processes (with application of solvents and/or catalysts in a high pressure and temperature environment) or carbon-rejection processes (carbonization or pyrolysis). Like the family of IDCL processes, it can produce both fuels and chemicals.

DCL processes date back to the work of Friedrich Bergius from 1912 to 1926, and commercial production began in Germany in 1926^{xxxix}. In 1931 Bergius was awarded a Nobel Prize for his work on chemical reactions under high pressure. By 1944, 12 DCL plants were in operation in Germany. The DCL process has been the subject of a significant body of R&D work since then, including major developments under both the U.S. Bureau of Mines and the U.S. Department of Energy (DOE).

Like other countries with vast coal reserves China had research activities in coal-to-liquids technologies dating back to the 1930s, and similarly reduced this activity when oil was cheap and plentiful and renewed interest in response to supply and price disruptions. In the 1990's China became a net importer of crude oil. Coal conversion to liquid fuels became a strategic energy supply issue and the incentive to renew development of coal-to-liquids became a priority.

In 1997 the Shenhua Group began their initial development of a DCL project. Shenhua's DCL project was initially discussed between the top leadership of the USA and China. The Chinese visited the United States' DOE and resulting from that visit, the coal liquefaction project was regarded as one of the major cooperation projects between the two countries. DOE introduced Shenhua to DOE's long-term technology partner (Hydrocarbon Technologies Inc. - HTI) in developing DCL in the US, and HTI immediately began experimentation on Shenhua's coal, and HTI signed a process license agreement with Shenhua Group for the direct coal liquefaction plant in China. However, it was ultimately decided that the DCL technology was too important to be controlled by a foreign entity and Shenhua negotiated the rights to apply the HTI technology and to further develop their own "China Shenhua DCL Technology." The plant construction was completed in 2008 and started operation in December 2008. The plant processes 6,000 tons per day of coal and produces 20,000 barrels per/day of liquid fuels (LPG, gasoline and diesel).^{xi}

A second DCL project in China was started in 2015 by Yanchang Petroleum Company at their Yulin City refinery. This plant processes 1,500 TPD of coal and petroleum derived oil (about 45 % of the feed is coal).

Synfuels China Technology Co. Ltd. has been developing a hydro-liquefaction technology, known as "Stepwise". This process has been tested with low rank coal^{xlii} and may offer opportunities for reduced cost liquid fuels and chemical production based on U.S. low rank coal.

Coal Conversion Outlook

Syngas production for synthetic fuels, fertilizer and methanol – including that produced from coal – is expected to continue to increase through 2030.^{xliii} Asia is expected to dominate the growth in coal-based syngas production.

The DCL process, which bypasses the intermediate step of producing syngas, may offer opportunities, notably with low rank coals which can present gasification challenges.

Carbon Products

Electrodes, Graphite Products and Carbon Fiber

Coal has a long history of use as a feedstock for the production of carbon materials. Parallel with this history has been R&D activities oriented toward coal use as feedstock for carbon materials. Coal products are used as feedstock for amorphous and graphite furnace electrodes used in metallurgical applications, activated carbon products and carbon fibers. New applications such as graphene and carbon foams can present new market opportunities for coal as a feedstock for these products.

The most significant international developments related to synthetic graphite products have included the diminishing U.S. production of coal-derived pitch products, along with needle coke shortages. Current U.S. production capacity of coal tar pitch is likely less than 250,000 MTPY, compared with world coal tar pitch production in 2016 estimated at 6.7 MMTPY, and projected at that time to grow to 8.1 MMTPY by 2020.^{xliii}

Another international development of note has been the tightening of the needle coke market. In addition to use for furnace electrodes, needle coke is used in the production of graphite for lithium-ion batteries. In 2012, the worldwide petroleum-derived needle coke market was estimated to be 1.2 MMTPY.^{xliiv} Demand for needle coke for battery applications has been growing, leading to a tight market.^{xliv} The demand for both furnace electrodes and graphite for batteries is expected to grow through 2028,^{xlvi} which, absent additional production capacity, is expected to further tighten the needle coke market.

While developments such as diminished domestic pitch production and tightening of the needle coke market will have potential impacts on U.S. production of synthetic graphite products, there have been significant R&D activities overseas related to both of these topics. In Japan, Mitsubishi Chemical Corporation developed pitch coke, anode coke and CF precursors based on coal tar (pitch-based fibers). In the case of pitch coke, the product is used in the production processes for semiconductors and solar panels.^{xlvii} The company manufactures carbon anodes for lithium-ion batteries and pitch for CFs, produced from coal products. While the majority of carbon fiber production is not based on pitch, this is notable as synthetic graphite products and carbon fibers can share a common coal-derived feedstock.

An additional development that has originated in Japan is the investment in two new CF plants in South Carolina (by Teijin and Toray Industries), adding production capacity in a region that has hosted CF production plants since 1981.^{xlviii}

Himadri Specialty Chemical Ltd. produces coal tar pitch and other carbon products, and has a significant R&D activity aimed at expanding their product offerings. Results include the development of special pitch products, including one that has been developed for aerospace applications. Development of anode materials for lithium-ion batteries is among the company's current R&D activities.^{xlix}

Amorphous carbon electrodes for ferroalloy and silicon metal furnaces, and cathodes for aluminum reduction furnaces, use calcined anthracite, produced in electric calcining furnaces. While U.S. production capacity for electrically calcined anthracite (ECA) has been disappearing, overseas ECA production facilities remain an important export outlet for U.S. anthracite producers.

While U.S. aluminum production from primary smelters has been declining for decades, worldwide primary aluminum production in 2016 was 59 MMTPY.¹ Were U.S. coal products to be available with the properties required of anode cokes (notably low ash content), this could result in the development of a new export market for the U.S. coal industry.

Activated Carbon

Environmental and health considerations are the key drivers of activated carbon use to provide clean air and water. Developing countries are expected to expand their activated carbon consumption as environmental controls are implemented. The global activated carbon market in 2017 was reported at \$2.8 billion.^{li}

The global activated carbon market is expected to grow to over \$6 billion by 2023. According to the IEA^{lii} global production of activated carbon was greater than 3.7 billion pounds in 2017. Production is documented by the U.S. International Trade Commission (ITC)^{liii} in China, India, Indonesia, Japan, Philippines, Sri Lanka, Australia, The Netherlands and Germany, in addition to the significant U.S. production discussed in Chapter 5. This important coal-derived product has several emerging growth markets.

Carbon Products Outlook

Worldwide growth in demand is forecast for the range of synthetic graphite products, including furnace electrodes and battery applications, as well as other products requiring the material such as refractories and shapes.^{liv} While needle coke derived from petroleum is preferred for high-end applications, such as ultra-high power (UHP) furnace electrodes^{lv}, needle cokes derived from coal find other applications. With the forecast growth in demand for premium needle coke, the development of coal-derived needle coke products for the high-end market could assist U.S. coal producers and manufacturers in accessing this market, where the product sells for a considerable premium.

The decline in U.S. coal tar pitch production has resulted in constraints in both supply and demand. However, increased demand due to global production of graphite products, absent dramatic reductions in demand from the worldwide aluminum industry, will likely at least maintain the market for pitch. The use of alternate technologies to extract pitch from coal within the U.S. may create export opportunities for the product.

Currently, carbon fibers are generally higher cost but CFs are experiencing the fastest growth rate in the overall fiber market. Pitch-based CFs offer greater strength than polyacrylonitrile (PAN)-based CFs. This provides an opportunity for coal to meet the high-strength-to-weight ratio needs in aerospace, automotive, civil engineering, military and motorsports.

Market opportunities for coal-to-products could allow for U.S. coal products to enter the value supply chains for significant and, in some cases, growing markets. Work has been undertaken in these areas with respect to U.S. coal by both the U.S. Bureau of Mines and DOE. Building on this body of research, which is reviewed elsewhere^{lvi}, could offer early opportunities to get research results into the marketplace, with attendant jobs benefits for the U.S. economy and coal industry.

Rare Earth Elements

International Rare Earth Element Research and Coal

Currently, the U.S. is virtually 100% import-dependent for raw materials for its rare earth element-based manufacturing sector, mostly from China. In May 2018, the Department of Interior (DOI) published its “Final List of 35 Minerals Deemed Critical to U.S. National Security and the Economy”^{lvii}, which was compiled in response to White House Executive Order 13817, “A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals.” Some items on the Critical Minerals list, such as vanadium and germanium, have been commercially extracted directly from coal products. In other cases, coal is used as a reagent in the extractive metallurgy processes used to produce these commodities.

The concept of producing REEs from coal, over/under burden and coal byproducts has attracted attention internationally. A review of the presence of REEs in coal measures worldwide was the subject of a publication by the China University of Mining and Technology and the Russian Academy of Sciences in 2012.^{lviii}

With respect to international technology development, activities have the potential to impact both REE extraction from coal, over/under burden, and coal byproducts, as well as the use of coal as a reagent in extractive metallurgy processing.

An example of the former – which would allow for REE extraction from REE-rich underclays – is the pressure leaching process developed by Orbite Technologies in Canada.^{lix} This process, for which a pilot plant has been constructed in Quebec, is intended to co-produce multiple products, including alumina, gallium, and scandium, along with an REE concentrate. Aluminum smelter feedstock, gallium and scandium, are also on DOI’s CM list.

International technology development activities have also involved coal use in REE extractive metallurgy. Frontier Rare Earths (Luxembourg) and Outotec (Finland and Germany) have developed an integrated, coal-based acid roasting and calcination process, currently envisioned for use at a REEs production project in South Africa.^{lx}

Rare Earth Elements Outlook

Rare earth elements that are commercially produced include 14 different elements that occur together in nature and are produced together. Different elements find uses in different applications and the market is complex. However, market forecasts are available for the suite of REEs in aggregate. Examples of these market forecasts are also work products of overseas research.

One forecast from China’s University of Science and Technology Beijing produced aggregate demand growth forecasts for REEs, ranging from 70% to 140% between 2012 and 2030.^{lxi} The growth in worldwide demand for REEs is expected to produce opportunities for new mineral sources. New extractive metallurgy operations that use coal in the process can also drive increases in world coal demand. Should sufficient REE concentrations be found in the U.S. coal reserves, this will create a new market for the materials produced by coal mining operations. The development of coal-based extraction technologies, in pyrometallurgical operations such as roasting and calcining, can produce new market opportunities for U.S. coal products.

The Metallurgical Sector

Coal products are used today in both ferrous and non-ferrous metals production worldwide. Many of the metallurgical processes that have resulted in the development of markets for U.S. coal product have been the result of overseas technology development activities. These activities date back to the original blast furnace installations in the U.S. that used hot blast furnace technology imported from the United Kingdom in the 19th century.

International technology development work resulting in markets for coal products in metallurgy applications include the following examples:

- The Waelz Kiln - This process was developed in Germany, originally for the recovery of zinc from low-grade ores. More recently, the listing of EAF dust, a steelmaking byproduct, under the Resource Conservation and Recovery Act (RCRA), has led to the adaptation of the Waelz kiln for the recovery of lead and zinc from a RCRA listed material. As such, elimination of hazardous waste became a new market of U.S. coal products.
- The Quebec Iron and Titanium (QIT Fer et Titane) (QIT) Process - Is a pre-reduction-electric arc smelting system for the production of pig iron and titanium-rich slag from ilmenite, and has resulted in a significant market for U.S. anthracite.
- The Basic Oxygen Furnace (BOF) - Also known as the Linz–Donawitz (LD) vessel, this oxygen-blown version of the Bessemer Converter was developed in Austria by a precursor of Voestalpine AG (Austria). In addition to being the workhorse converter for integrated steelmaking worldwide, practices have developed where coal products are added directly to the BOF, to allow for higher scrap charges to the converter. This has resulted in a new application for U.S. coal products.
- Oxygen/Carbon Lance Technologies for EAF Steelmaking - The injection of coal products with oxygen into an EAF can speed up scrap melting, reduce tap-to-tap times, and reduce electric power consumption. In the U.S., the electric arc furnace accounts for two-thirds (2/3) of domestic steel production. An example system was developed by Danieli (Italy). While EAF steelmaking eliminates the need for the blast furnace and its coke requirements, the adaptation of EAF lance coal injection by the steel industry has led to the development of a new coal market.
- The Elkem Electric Calcining Furnace - The Elkem (Norway) calcining furnace is used to calcine anthracite for use in cathodes and ramming paste at primary aluminum smelters, as well as for electrodes for ferroalloy and silicon metal smelters. This development has led to a significant market for U.S. anthracite.
- Top Submerged Lance Technology - This is an Australian development with numerous applications in non-ferrous metallurgy, including the production of lead, zinc, copper and nickel. Depending on the application, coal can be a requirement. One type, the Ausmelt system, has been installed 64 times at worldwide locations.

Metallurgical Applications Outlook and Opportunities

New extractive metallurgy technologies are continuously under development worldwide. These have had a nearly two century impact on the U.S. coal industry and new developments can continue to provide new markets for U.S. coal products. The production of some metals can be expected to grow as new applications are found, notably in applications such as electronics.

Worldwide technology developments can provide opportunities to leverage additional work aimed at optimizing new processes around characteristics of U.S. coal products, such as:

- Silicon metal smelting, where low ash coal with special properties is required.
- Carbothermic aluminum reduction process development, as an alternative to the Hall-Heroult Process.
- Coal-based roasting processes for high value metals, such as the REE process discussed earlier.
- Direct steelmaking processes.

Summary: How Technology Development has Expanded Coal-to-Products Markets Internationally

International technology development activities have resulted in the growth of substantial markets for coal in non-conventional uses, such as chemicals, fertilizers, fuels, REEs and other products. While coal products are used in some applications in the carbon industries, there is potential for market growth in that sector through R&D activities, notably involving the production of needle coke and anode coke, and pitches as precursors for CFs and other carbon products.

International technology development in the extractive metallurgy field has resulted in expanded market reach for U.S. coal products, notably in non-ferrous metals production.

Chapter 5. Historical Perspective on U.S. Coal-to-Products Efforts

Key Findings

- Coal has a long history in the U.S. as a versatile carbon feedstock used for production of various products ranging from chemicals, synthetic natural gas, metals and building materials, to plastics, medications and photographic film.
- Abundant, low-cost U.S. coal reserves, in combination with both advanced material and advanced manufacturing technologies, hold significant promise for the future use of coal as a feedstock for carbon-based, value-added products, including new carbon products, chemicals, fuels, critical minerals and rare earth elements key to national security interests.
- Historically, U.S. coal conversion and coal-to-products initiatives have achieved varying levels of success. The most successful efforts have resulted from cooperative public-private partnerships. Among the factors that have delayed or hindered initiatives are the risks and costs associated with First-of-a-Kind (FOAK) technology deployments, changing market conditions, extensive environmental and construction permitting requirements, and difficulties obtaining project financing.
- Redirecting the use of U.S. coal resources into new markets outside of power generation and steel/coke-making has potential to open up new domestic and export markets for the U.S.

Introduction and Overview

Coal is a very versatile feedstock and technologies exist to convert coal by various means into almost any end product achievable from oil or natural gas, and in some cases into products unique to coal. Development of these coal technologies reach back to the earliest years of U.S. republic and have been driven over time by a combination of private industry funding, as well as public funding from state and federal governments and agencies, and academia.

Historically, coal in the U.S. has been used as feedstock for chemical, carbon and metal products. Coal combustion byproducts have, among other uses, been incorporated into cements and concrete mixes used in construction. The use of coal products in fertilizer production has added it to agricultural value chains. Consumer products derived from coal span a wide spectrum of products including photographic film base, performance polymers, flat-screen televisions, pain relief medications, adhesive tape, high-end fashion fibers, shampoo, wood preservatives, graphite, activated carbon and carbon fibers (CFs).

In the U.S., the production of numerous commodities was, in the past, based on coal feedstocks. Technology and infrastructure advances associated with petroleum and natural gas over time yielded more favorable and cost-effective competitive positions of those feedstocks compared with coal in a number of domestic markets, such as chemicals and fuels production. In other U.S. markets – notably those associated with metals production – the introduction of newer technologies, such as the electric arc furnace (EAF), created an alternative to the traditional large volume coal product (furnace coke in the case of metals). Ironically, the availability of low-cost electric power from coal in the U.S. also played a role in the adoption of EAF technologies.

U.S. coal products are well established in domestic power generation and steel/coke markets, as well as in export markets based on these applications. Coal also has some inherent advantages in non-fuel coal markets, including the offering of a full range of coal ranks (involving volatile matter and moisture contents). Recently, coal-based power generation has been under domestic market pressure due to competition from cheap abundant natural gas. U.S. coal consumption has gone from a peak of about 1.2 billion tons to 700 million tons in recent years and could fall to as low as 400 million tons by 2030.^{lxii} Reducing the production and transportation costs and/or improving the quality of various coal products can help enhance the competitive positions of the end uses of coal-derived products, in turn helping to preserve these markets for U.S. coal producers and improving the competitive position of U.S. coal for these and other applications in export markets.^{lxiii}

The continued abundance of low-cost U.S. coal reserves and recent advances in technology are once again favorably positioning coal as a potential feedstock for higher value-added products, particularly those that are heavily carbon-based, and as a source of critical minerals (CMs), including rare earth elements (REEs). Potential technology advances related to coal upgrading are also making U.S. coals more attractive for export markets.

This chapter addresses the historical perspective and recent developments related to U.S. efforts for coal-to-products applications.

Coal Beneficiation

Overview

Coal beneficiation, as included in this report, refers to upgrading coal quality characteristics. Coal quality requirements for non-conventional markets can differ significantly from those required for power generation applications. Coal in the latter use is a source of energy with its calorific value being the key quality parameter. Coal quality requirements for non-conventional markets, on the other hand, are governed by its use in equipment such as gasifiers, its use as a metallurgical reductant, and its use as a source of carbon.

Coal ash content/composition, volatile matter content and moisture will all have an effect on coal utilization for fuels, chemicals, carbon products and extractive metallurgy. These coal quality characteristics are addressed in Appendix A.

R&D activities associated with coal upgrading have a long history and range from basic research to attempts at commercialization. Basic research aimed toward improved understanding of physical phenomena in commercial coal prep systems has led to substantial operational improvements, notably led by the work of the U.S. Bureau of Mines and Department of Energy (DOE).

An abundance of fundamental information has been generated on the behavior of coal in thermal processing systems and on the subject of coal interactions with solvents.^{lxiv} Many successful commercial technology introductions have occurred over the past couple of centuries, often involving coal mining companies working in cooperation with federal agencies. More recent technology development efforts have led to a number of demonstration projects.

Market conditions, notably the potential for new applications for materials produced through coal mining, may create new opportunities for processes that have been either the subject of R&D or past commercial application. Examples could include the extraction of pitch for CF applications, or the production of coal with a very low ash content.^{lxv}

The DOE published a comprehensive report^{lxvi} in March 2018 on the history and opportunities associated with coal upgrading technologies. This report informed much of this chapter section and can be referenced for additional details on the subject.

Physical (Gravity) Separations

The dominant method by which coal upgrading has taken place in the U.S. coal industry is through physical or gravity separation of non-coal particles from run of mine material, which results in an ash content and sometimes a sulfur (S) and/or mercury (Hg) content reduction of the finished coal product.

Physical separations can be broken into several major categories:^{lxvii}

Dry Processes	Water-Only Processes	Dense Medium Processes	Froth Flotation
<ul style="list-style-type: none"> • Crushing, screening, sorting • Dry spirals • Air tables • Electrostatic • Magnetic • X-ray luminescence 	<ul style="list-style-type: none"> • Jigs • Concentrating tables <ul style="list-style-type: none"> ○ Bumping table ○ Reciprocating motion table • Hydrocyclones • Wet spiral separators 	<ul style="list-style-type: none"> • Static bath • Dense medium cyclones • Dense medium types: <ul style="list-style-type: none"> ○ Sand ○ Magnetite ○ Pyrite cinders ○ Ferrosilicon ○ Organic liquids ○ Salt solutions 	<ul style="list-style-type: none"> • Traditional tank systems • Column flotation systems • Various additives used to enhance performance

These separation processes have been developing for over a century. In the 1800s, dry processes predominated, including crushing and screening, often with hand sorting of coal from rock. Mechanical dry processes were introduced starting in the early 1920s. More modern dry separation processes include electrostatic separation processes, dry magnetic processes and X-ray transmission sorting processes.^{lxviii} Electrostatic separation has been used to make low ash feedstock for carbon products and has been examined for both coal upgrading and recovery of REEs from coal byproducts.^{lxix}

Water-only separation systems work with suspensions of the feedstock in water. The earliest of these processes, jigs, were introduced in the early 1870s^{lxx} and are primarily used for cleaning coarse coal sizes.

Dense medium systems, now used broadly for coal upgrading, use liquids with specific gravities greater than water to create a suspension. The first dense medium system in the U.S. was installed in 1921.^{lxxi} More recent R&D work on dense medium systems has included attempts to separate coal and rock with liquid carbon dioxide^{lxxii} and the development of a process using micronized magnetite.^{lxxiii}

Froth flotation, selectively removes as a floating product the solids that adhere to introduced bubbles. The use of such froth flotation separation dates to the late 19th century.^{lxxiv} U.S. commercial application for coal cleaning dates back to 1930.^{lxxv}

As of 2015, there were 268 coal prep plants in the U.S., with an aggregate installed capacity of over 200,000 tons per hour (TPH). Current physical separation methods include dense medium vessels, jigs, and large-diameter dense medium cyclones for coarse coal (>10 millimeter (mm)), dense medium cyclones and jigs for intermediate (10 - 1 mm) sizes, spirals and water-only cyclones and tables for fines (1 - 0.15 mm), and flotation for ultra-fines (<0.15 mm).^{lxxvi}

Thermal Treatment Processes

A reduction in coal moisture by thermal drying improves the heating value of the coal, reduces coal flow to boilers, improves unit efficiency, plant operation and economics, and reduces emissions. Configurations for coal thermal drying systems include fixed bed, rotary bed, fluid bed, and entrained flow systems.^{lxxvii} However, many traditional thermal processes were either mechanically complex or required costly primary energy or steam to remove the moisture. Thermal drying of bituminous and anthracite coal products has been a commercial practice for decades, including for the production of carbon products and steel.

Recent innovations in coal drying have included the successful demonstration of the use of low-grade power plant heat for moisture reduction of lower rank coals.^{lxxviii} Advanced thermal drying of low rank coal has been in continuous commercial practice by Great River Energy since 2009.^{lxxix} This DryFining™ system, the result of a DOE-sponsored demonstration, uses low-grade heat from a power plant to dry 1100 TPH of lignite in a 2-stage moving fluid-bed drying process and has operated with over 95% availability.^{lxxx}

Carbonization processes in the U.S. are currently used for the production of metallurgical coke. Low-temperature carbonization was first commercially practiced in 1933^{lxxxix} and in the 1950s collaboration among the U.S. Bureau of Mines, Alcoa, and Texas Power and Light led to the construction of a prototype low temperature carbonization system for lignite.^{lxxxii} The plant was built to produce tar for market studies, and a pilot plant was added to investigate the upgrading of recovered tar to salable products.^{lxxxiii} More recent developments in low-temperature carbonization have included demonstrations of the liquids from coal (LFC) and advanced coal conversion process (ACCP) technologies.^{lxxxiv}

Thermal processes at temperatures above those for carbonization can be used to produce carbon aggregates. The typical application is mixing with a binder and further high-temperature processing to produce electrodes and refractories. Calcination is used commercially to heat treat carbon products, with an attendant improvement in electrical conductivity.^{lxxxv}

Research into graphitization has included the use of coal, notably anthracite. The current aggregate used in graphite electrode formulations – needle coke typically derived from petroleum – has been subject to adverse price and availability constraints. Graphite electrodes are used in the U.S. steel and aluminum smelting industries, and any electrode cost reductions that could result from the production of coal-based graphite electrodes could help improve the competitiveness of the U.S. domestic steel industry.^{lxxxvi}

Chemical Extraction Processes

Chemical extraction processing of coal products involves the use of a solvent to selectively extract constituents from the rock. Extraction with organic solvents can be applied to produce organic products such as liquids or pitches from coal, and inorganic solvents can be used to extract metal values and remove mineral constituents associated with coal sediments.

The application of inorganic solutions to leach metal values from rock is a commercial practice that dates back over 100 years.^{lxxxvii} Inorganic solvents have been used at an industrial scale for the production of low-ash anode carbon for aluminum smelting. Extraction of coal with organic solvents dates back to U.S. Bureau of Mines work in the early 20th century.^{lxxxviii} Extraction with organic solvents at elevated temperatures and pressures can be used to produce pitch^{lxxxix}, and when hydrogen is also added to the system can be used to produce feedstocks for liquid transportation fuels (e.g., DCL).

Chemical extraction processes offer the potential to significantly broaden the slate of products that can be produced at U.S. coal mines.

New Technology Developments

Examples of some of the more promising new technology developments in the coal upgrading area include the following:^{xc}

- Clean Coal Technologies, Inc. Pristine™ Technologies^{xcj}- Processes that remove moisture and volatiles from lower rank coals, then reabsorb some of the volatiles into coal pores to produce a stable high quality and cleaner burning dry coal product.

- LP Amina BeneficiationPlus™ Process^{xcii}- A thermal process that pyrolyzes coal in a fluid-bed system, producing liquids, gases, and a dry, partially devolatilized char. Liquids and gases can be refined to make value-added products or generate heat or power.
- Western Research Institute's WRITECoal™ Process^{xciii}- A thermal process for water and Hg removal. Products are a dried power plant fuel with reduced Hg content and recovered water that can be used for process purposes. As an alternative to power generation, the solid process product can be pyrolyzed and the volatile products processed to produce feedstock precursors for production of CF and other carbon products.
- H Quest Vanguard, Inc.'s Wave Liquefaction™ Process^{xciv}- This thermochemical process involves use of microwave/radio frequency (RF) plasma to enable rapid pyrolysis (carbonization) of coal and natural gas in a modular reactor to produce value-added liquid products and a char that can be used as fuel or for carbon product applications.
- Great River Energy's DryFining™ Process^{xcv}- This process integrates thermal processing and physical separation. The heart of the system is a two-stage moving fluid-bed dryer accomplishing two functions: it cleans the coal by removing a significant portion of S and Hg from the coal in the first stage via an air jig and dries the coal in the second stage. The cleaning function, accomplished by gravitational segregation in a fluidized bed, distinguishes this technology and provides a very important co-benefit of emissions reduction. As mentioned previously, this technology has been in successful operation using low-grade heat from a power plant since late 2009.
- Minerals Refining Company's Hydrophobic-Hydrophilic 2-Liquid Separation Process^{xcvi} – This novel process, developed at Virginia Polytechnic Institute and State University, utilizes a combination of hydrophobic and hydrophilic liquids to separate very fine (too fine for froth flotation) coal and mineral particles from non-coal/ash particles and provides a dry coal product following solvent recovery.

In addition to these technology developments, the DOE National Energy Technology Laboratory (NETL) has been developing an American Coal Properties Database, drawing on data and expertise from the DOE National Labs and academia to provide detailed technical information on the impact of coal properties and composition on power plant performance and emissions. The database will centralize detailed information on U.S. produced coal to facilitate its use domestically and abroad by helping potential users understand the impacts of its use in a wide variety of applications including value-added products from coal.^{xcvii}

Coal Conversion to Fuels and Chemicals

Early History

U.S. development of coal-to-products market applications for coal began as early as 1816, when the Gas Light Company of Baltimore was founded and began providing town gas (early SNG) made from coal to light the streets of Baltimore, Maryland.^{xcviii} By the 1850s, many small to medium-sized cities had a coal-based gas plant to provide for street lighting and eventually for gas cookers and stoves. Byproducts of town gas production were eventually recovered and utilized for chemical and dye applications. However, developments in oil and gas exploration led to the eventual phase out of coal-based town gas by the early-mid 1900s.

In the winter of 1922-23, a major disruption in U.S. coal supply due to labor disputes led to an increased shift by consumers to oil and natural gas.^{xcix} Developments from World War I had also led to an increased use of petroleum fuels for vehicles and aircraft. This placed a strain on domestic oil and gas production and led to concerns about long-term resource availability of oil and gas. At the same time, new developments were occurring in Germany for the conversion of coal-to-liquids (CTL) fuels through processes such as the Bergius direct coal liquefaction (DCL) direct coal hydrogenation process and the Fischer-Tropsch (FT) indirect coal liquefaction (ICL) process for conversion of syngas (from coal) to liquid fuels.

The U.S. Bureau of Mines took the lead in exploring two potential substitutes for petroleum: liquid fuels from oil shale and liquid fuels from coal. At the Pittsburgh Experiment Station, chemists organized a small group to work on CTL conversion, and by 1926, had equipped a laboratory for producing small quantities of water gas (consisting of CO and H₂) and observing how the gas components reacted to different catalysts at varying temperatures and pressures.^c

The synthetic liquid fuels group initially chose to study the synthesis of alcohols (such as methanol) and liquid hydrocarbons from water gas. Its experiments verified that the process could yield methanol of high purity and that this methanol could be further converted into DME that had potential as a motor fuel. The synthetic liquid fuels group also began investigating the Bergius direct coal hydrogenation process in 1928 and did preliminary work on the conversion of water gas into methane. However, the coming of the Great Depression halted the research program. Some work on low-temperature coal carbonization, synthetic methanol, and the Bergius-I. G. Farben process continued, but a shortage of funding after 1931 obliged the scientists to concentrate on other projects. The economic collapse coincided with the great petroleum discoveries in Oklahoma and East Texas, with the result that energy prices fell and the likelihood of petroleum shortages seemed more remote than ever.^{ci}

Concerns over Germany's military build-up prior to World War II, and use of coal to fuel it, led U.S. Secretary of the Interior Harold Ickes to identify coal hydrogenation as a top research priority for the Bureau of Mines, and in 1935 he asked Congress to fund a 100 pound per day hydrogenation pilot plant at the Pittsburgh Experiment Station and to conduct a hydrogenation assay of domestic coals. Crude oil from the pilot plant yielded up to 7 gallons per day of gasoline. The hydrogenation assay confirmed that hydrogenation could work across a wide range of coals, indicating that most of the country's vast coal reserves qualified as raw material for synthetic liquid fuel production.^{cii}

Synthetic Liquid Fuels Act (1944)

Following War World II and Germany's successful program for converting coal to liquid fuels, the U.S. Synthetic Liquid Fuels Act was approved on April 5, 1944.^{ciii} The Act authorized \$30 million in funding over a five-year period to construct and operate demonstration plants to produce synthetic liquid fuels from coal, oil shale and renewable raw materials. The Act directed that the demonstration plants be of a size suitable to provide the necessary cost and engineering data for the development of a synthetic liquid fuel industry. In 1948, Congress extended the Act to eight years and doubled the funding and in 1950, Congress approved a second amendment adding another \$17.6 million.

To begin implementing its new program, the U.S. Bureau of Mines expanded laboratory work it had been conducting near the Carnegie Institute. The work was transferred to new laboratories created in Pittsburgh, Pennsylvania and Morgantown, West Virginia. In addition, two coal-to-oil plants were constructed at a renovated site in Louisiana, Missouri:

- A 200 BPD direct coal hydrogenation plant that produced 1.5 million gallons of synthetic gasoline from 1949-1953.
- An 80 BPD FT plant, started up in 1951 that transformed coal into a gas, then chemically rearranged the gaseous molecules into liquid fuels and chemicals, and produced 40,000 gallons of liquid products.

The Morgantown facility also built and ran a pilot scale gasifier capable of processing 500 pounds per hour of coal. In parallel to these efforts, in 1952, the nation's first privately built and operated coal hydrogenation plant began operating at Institute, West Virginia. Constructed by the Carbide and Carbon Chemical Company (later to become Union Carbide), the plant could process 300 tons of coal daily. From 1952 to 1956, the plant produced chemicals from coal.

In 1953, Congress ceased funding for the Synthetic Liquid Fuels Program as America's energy sights and supplies were shifted towards massive oil reserves that had been discovered in the Middle East. For the remainder of the 1950s and early 1960s, coal and synthetic fuels research was relegated to low-priority fundamental studies, but the knowledge gained during this period proved to be valuable when the nation's coal research program was rejuvenated in 1961, with creation of a new Office of Coal Research within the U.S. Department of the Interior (DOI).

1970s Oil Crises

The oil crises of the 1970s – results of the 1973 Arab Oil Embargo and the 1979 Iranian Revolution – led to severe shortages of oil, and drove prices to record levels. In 1975, the Energy Research and Development Administration (ERDA) was created and brought together for the first time the major programs of research and development for all forms of energy.^{civ}

From the DOI came the Office of Coal Research and from the Bureau of Mines the energy centers and the coal liquefaction and gasification programs. In 1975, the first national energy plan from ERDA was developed, including plans to accelerate capabilities to extract gaseous and liquid fuels from coal and shale.

Starting in 1977, the energy crisis stimulated several major new pieces of legislation, including the Energy Security Act of 1980 (ESA). On April 18, 1977 President Jimmy Carter announced a new National Energy Plan. His plan called for the establishment of an energy department in the executive branch, in order to assure coordinated and effective administration of federal energy policy and programs. In August of that year, Congress enacted the DOE Organization Act, which established the U.S. DOE, supplanting the short-lived ERDA.^{cv}

The new DOE embarked on a major DCL campaign which lasted over two decades. Results of this campaign are described in a report prepared by experts from Consol Energy and Mitretek Corporation and published by DOE in 2001.^{cv} In the report, the experts analyzed the costs and benefits of the DOE DCL effort and concluded that the program achieved many of its objectives, resulting in substantial improvements in process performance (e.g., yields), economics and the risk level reduction associated with commercial deployment, to the extent that DCL represented a technically available option for the production of liquid fuels. In addition, considerable research was directed toward a better fundamental knowledge of coal chemistry, and to identify and explore novel liquefaction concepts.

The ESA created the congressionally chartered United States Synthetic Fuels Corporation (SFC). The SFC was established to create a financial bridge for the development and construction of commercial synthetic fuel manufacturing plants that would produce alternatives to imported fossil fuels. The ESA established a national goal of achieving a synthetic fuel production capability of at least 500,000 BPD of crude oil by 1987 and at least 2,000,000 BPD of crude oil by 1992. The projects were to convert the nation's coal, oil shale, and tar sands resources into synthetic fuels as substitutes for natural gas and petroleum. Congress planned to fund the corporation with up to \$88 billion during its expected period of existence from 1980 to 1992. The SFC had authority to provide financial assistance via purchase agreements, price guarantees, loan guarantees, loans and joint ventures. The SFC funded four synthetic fuels projects, none of which survive today, but at least two of the projects (Coolwater and Dow Syngas projects) helped support future coal gasification projects in the U.S. and abroad. With the election of Ronald Reagan as President, coupled with a return to more normal oil prices and supply, emphasis on the SFC diminished and it closed its doors in 1986.^{cvii}

However, the 1970's oil crises did spur two ultimately successful commercial coal conversion deployments and served as a driver for several other early coal conversion developments. Eastman Kodak Company, concerned that it would lose access to the oil needed for producing its valuable photographic film base, decided to construct a coal gasification facility at its Kingsport, Tennessee manufacturing site (now Eastman Chemical Company) that at the time used Texaco-design (later acquired by GE) gasifiers to produce syngas for conversion into methanol and acetyl chemicals (methyl acetate, acetic acid, and acetic anhydride). Acetyl chemicals are attractive for coal-to-chemicals (CTC) conversion because they are able to utilize a high percentage of the coal's carbon, reducing by-product CO₂ emissions. The Eastman facility started up in 1983 and has been very successfully operated ever since that time. The plant has had one of the best coal gasification operating records in the world, consistently achieving on-stream availabilities of 98-99% and achieving over 150% of its original nameplate capacity.^{cviii} In 1997, a DOE-sponsored liquid-phase methanol process commercial demonstration facility was constructed and operated at the Eastman site (further described below).

In parallel to the efforts by Eastman, the Great Plains Synfuels Plant (Synfuels Plant), owned and operated by Dakota Gasification Company (Dakota Gas) – a subsidiary of Basin Electric Power Cooperative, and located near Beulah, North Dakota – began operation in 1984.^{cxix} The project benefited from a DOE federal loan guarantee, which enabled the project to move forward after struggling to obtain adequate commercial financing for such an FOAK project.

DOE also owned and operated the facility for a brief period (July 1986 until December 1988) after the original financing fell through and before selling it to Dakota Gas.^{cx} The Synfuels Plant converts North Dakota Lignite into pipeline quality natural gas and is integrated with the adjacent Antelope Valley Station (AVS) electrical generating plant. The Synfuels Plant produces and sells more than 54 billion standard cubic feet (SCF) of SNG per year.^{cx} In addition, Dakota Gas has an ever-expanding product line that has helped improve the economics of the plant and reduce the sensitivity to natural gas prices. These non-SNG products include liquid nitrogen and krypton and xenon gases captured from the air separation unit, fertilizers (including anhydrous ammonia, ammonium sulfate, and urea), CO₂, and chemicals such as dephenolized cresylic acid, naphtha, phenol, and tar oil.^{cxii}

The Synfuels Plant began selling CO₂ for enhanced oil recovery (EOR) and geologic storage in the Weyburn and Midale oil fields in Southern Saskatchewan in 2000, transported via a 205-mile pipeline with a daily capacity of up to 165 million SCF. About 2.5 million tons of CO₂ per year is captured, which is ultimately stored in geologic formations as a result of the EOR operations. Additional targets for CO₂ EOR from the Synfuels Plant, as well as from potential carbon capture at nearby power plants, are under consideration in conventional oil fields of the region. Technology for use in the Bakken and Three Forks shale oil formations is under development.^{cxiii}

Clean Coal Technology (CCT) Demonstration Program (1987)

The CCT Demonstration Program, adopted in 1987, was established to demonstrate the commercial feasibility of new advanced coal-based technologies with enhanced operational, economic, and environmental performance. The program consisted of 40 cost-shared projects selected through five competitive solicitations. These projects resulted in a combined commitment by the federal government and the private sector of more than \$5.6 billion (DOE's cost-share was approximately 34%).^{cxiv} Two of the most successful projects produced liquid fuels from coal:

- **ENCOAL® Liquids from Coal (LFC™) Process**^{cxv} – This 1,000 TPD mild coal gasification facility was built near Gillette, WY in 1992. The process technology utilized low-sulfur Powder River Basin (PRB) coal to produce two new fuels: Process-Derived Fuel (PDF™) and Coal-Derived Liquids (CDL™). The products, as alternative fuel sources, are capable of significantly lowering current sulfur emissions at coal boiler sites. CDL is also an acceptable substitute for heavy industrial fuel without further processing, or can be fractionated into major constituents, including valuable chemicals. The facility processed 246,900 tons of coal and produced 114,900 tons of PDF™ and 4,875,000 gallons of CDL™.

- Liquid-Phase Methanol (LPMEOH™) Demonstration Project^{cxvi}— This commercial demonstration project was sponsored by an Air Products and Chemicals, Inc. and Eastman Chemical Company partnership. The project utilized Air Products' LPMEOH™ technology and was located at Eastman's chemicals-from-coal complex in Kingsport, TN. The process was developed to enhance electric power generation using integrated gasification combined cycle (IGCC) technology, by co-producing methanol when full power generation capacity was not needed. The demonstration project reached nameplate capacity (260 TPD of methanol) just four days after initial startup and produced more than 100,000,000 gallons of methanol that Eastman used to produce valuable acetyl chemicals, making it one of DOE's most successful demonstration projects. The facility is still in commercial operation today.

Other Private Industry Initiatives

In mid-2000, Farmland Industries started up a 1,084 TPD, petroleum coke-fueled gasification facility to produce hydrogen for conversion to ammonia and urea ammonium nitrate fertilizers. The facility utilized the original gasifier from the SFC's Coolwater project, but in modified form, as one of its two gasifiers. Although the facility has been primarily fueled by petroleum coke, it is essentially identical to coal-fueled facilities and thus worthy of mention here. The facility is now operated successfully at high on-stream availability by CVR Partners LP, a subsidiary of Coffeyville Resources.^{cxvii}

In the past couple of decades, there have been a number of other projects for conversion of coal (or in some cases coal and/or petcoke) to fuels or chemicals that progressed to significant levels of project development, but each failed to reach commercial reality because of cost economics and economic conditions. Some of the most promising of these proposed projects were:

- Eastman Chemical Company's proposed polygeneration project in Beaumont, TX.^{cxviii} Planned to produce hydrogen, methanol, ammonia, and electric power and steam from over 2 MTPY of coal and/or petcoke, with 90+% CO₂ capture for use in EOR. The project made it through detailed front-end engineering and design (FEED) and received a number of federal and state incentives, including a DOE loan guarantee, before being dropped as a consequence of the 2008 financial collapse.
- Summit Power's proposed Texas Clean Energy Project near Odessa, TX.^{cxix} Planned to co-produce 400-Megawatt (MW) of electric power and 700,000 TPY of urea, along with 90% CO₂ capture for use in EOR. The project received a \$450 million award from DOE under the Clean Coal Power Initiative (CCPI) and proceeded through FEED and permitting before folding due to construction cost escalation, key partnership changes, and failure to obtain final financing.
- A proposed Lake Charles Methanol, LLC project near Lake Charles, LA.^{cxx} Planned to produce methanol, hydrogen and capture CO₂ from pet coke and/or coal. The project received a conditional commitment from DOE in 2016 for a loan guarantee, but has languished since that time with an uncertain future.
- DKRW Energy LLC's proposed ICL plant near Medicine Bow, WY.^{cxxi} Planned to produce transportation fuels, with CO₂ capture for EOR. First conceived in 2004, the project struggled amid numerous changes and delays and was indefinitely suspended in 2016 after oil prices collapsed and failed to recover to revenue levels sufficient to justify the project's expected cost.

- Baard Energy's proposed 50,000 BPD coal-to-diesel project in Ohio:^{cxxii} The project received approved permits, but faced a number of obstacles, including declining oil prices, and was officially suspended in 2011.

There have been a number of other U.S. coal conversion projects besides the above that were also proposed and developed to various stages before being suspended.

Recent DOE Initiatives

In the past decade or so, DOE has come to recognize the growing potential value of coal as a conversion feedstock, versus its primary use as a fuel for power and steam generation. The DOE efforts to support utilization of coal for conversion to fuels or chemicals have primarily been focused in the advanced gasification program and/or in the coal/biomass to liquids (CBTL) program (recently combined under the gasification program).

A number of Funding Opportunity Announcements (FOAs) have included areas of interest related to coal conversion. Recent DOE efforts to drive development of radically engineered modular systems (REMS) for gasification have a side benefit of reducing the economy of scale of gasification technology, thus making it more economically attractive for coal conversion projects that often tend to be smaller in overall scale than large power generation projects.^{cxxiii} A recent DOE NETL project award was made to CarbonFuels, LLC to employ their novel Charfuel® Coal Refining Process at its existing, permitted 18 TPD pilot plant, to refine coal and produce an upgraded coal product and a number of organic and inorganic coproducts, in order to produce engineering and product data that can be used to design a commercial-scale integrated facility.^{cxxiv}

Coal to Carbon-Based Products

Overview

Carbon products such as pitches, foams, fibers, and graphite have been produced over many years using petroleum cokes derived from the production of fuels and chemicals. Germany in World War II, and South Africa in the era of oil embargos, successfully demonstrated that coal can be transformed to fuels and chemicals. Applied research on the use of coal to produce solid carbon-based products have been conducted by many academic and industrial teams. Specific topics of interest are to determine if products made from coal have better properties than the same products produced via petroleum routes, as well as the economics of such processes.

Coal tar pitch is produced from a byproduct of coke making (coal tar distillation). As noted in Chapter 4, U.S. coal tar pitch production has been declining, along with needle coke shortages, likely due to a combination of byproduct coke plant closures and reduced primary aluminum production in the U.S., producing constraints in both supply and demand. A 2008 estimate of U.S. coal tar distillation capacity was in the range of 1.1 MMTYPY.^{cxxv} Since then two of the cited plants, in Pennsylvania and West Virginia, have closed, further reducing the distillation capacity by half. Assuming a pitch yield of 50% of the distilled tar, the current U.S. production capacity of coal tar pitch is likely less than 250,000 MTPY. By comparison, world coal tar pitch production in 2016 was estimated to be 6.7 MMTYPY and estimated at that time to grow to 8.1 MMTYPY by 2020.^{cxxvi} While increases in coke plant coal tar production in the U.S. may not be on the horizon, the use of alternate technologies to extract pitch from coal within the U.S. may create export opportunities for the product.

Steam-activated carbon is produced in the U.S., primarily from lignite, bituminous, and subbituminous coal feedstocks. Manufacturing capacity has grown over the past decade, with capacity over 500 million pounds per year (0.25 MMTPY) in 2017 and a market size of about \$500 million.^{cxxvii} This corresponds to potential coal consumption on the order of 0.7 to 1 MMTPY. Domestic capacity exceeds actual production, with an overall production of about 71% of capacity in 2017. Historical industry, Electric Power Research Institute, U.S. Environmental Protection Agency (EPA), and DOE initiatives have enabled the development of new applications for activated carbons, expanding its domestic market and enabling the development of new products and formulations, such as for Hg capture emissions control. Both domestic and worldwide markets for activated carbon are expected to grow over the next few years, and capturing this share for U.S. suppliers and maintaining their competitiveness will depend on continued product and application development.

Such market opportunities could allow for U.S. coal products to enter the value chains for significant and, in some cases, growing global markets. Work has been undertaken in these areas with respect to U.S. coal by both the U.S. Bureau of Mines and DOE.

New market opportunities can extend the reach of U.S. coal products outside of traditional markets, notably where these products compete with petroleum products. These include the processing of coal into feedstocks for CF, graphite, and graphene production. These precursors can represent a significant product value compared with feedstock costs. Industrial interest in CFs is growing, as evidenced by the recent investment by Japan in two new CF plants in South Carolina (see Chapter 4 under Carbon Products section for more details).

In addition, potential exists for the use of coal in the value chains of products such as anodes for aluminum smelters and graphite furnace electrodes for the EAF-based portion of the steel industry. These represent research opportunities toward the development of new markets. Such development efforts have been and are being led by combinations of academia, federal agencies such as DOE, and industry.

The manufacture of graphite products requires very high process temperatures, use of binders such as pitches derived from petroleum as well as from coal tar⁷⁴, and aggregates that include needle coke (petroleum product) and cokes produced from the carbonization of coal tar pitch.^{cxxviii} Notable among graphite products are furnace electrodes for the steel industry (EAF application). The reliance of the graphite electrode industry on petroleum-derived needle coke has recently been an area of concern, as constraints in needle coke supply have helped drive an unfavorable electrode cost and availability situation in the steel industry.^{cxxix} This situation presents opportunities for the substitution of coal products for petroleum products in the graphite manufacturing process. Graphite production using coal as an aggregate and graphitization of coal itself have been demonstrated in the laboratory^{cxxx} and some process-related R&D may be required to fully match the properties of other graphite products. There is also the potential for the manufacture of a needle coke product from coal-derived pitch, especially pitch that has been solvent-extracted from coal^{cxxxi}, rather than pitches produced through distillation of coal tar recovered from carbonization (i.e. from byproduct coke production).

Academic Initiatives

The DOE's Office of Fossil Energy (FE) entered into long-term collaborative agreements with two groups – consisting of academic institutions and industry participants – to advance technologies for producing carbon products from coal. The Consortium for Premium Carbon Products from Coal (CPCPC) was one such program, led by Penn State over a period from 1998 to 2010.^{cxxxii} A related program was conducted by West Virginia University (WVU) from 2003 to 2009.^{cxxxiii} Recently, the Massachusetts Institute of Technology (MIT) has also been doing leading-edge research into utilization of coal as a feedstock for advanced carbon-based materials.^{cxxxiv}

The results of these low technology readiness level programs demonstrated that coal products such as pitches for electrode manufacture, foams for insulation, fibers for enhanced strength of light-weight materials and other products, such as graphite and carbon black, could be made economically from coal using advanced chemical and heat-based extraction processes. As with the DOE investments in coal-to-liquids programs, the funding provided to academic researchers also resulted in the development of NextGen researchers and technologists to succeed our aging workforce of coal chemistry experts.

Industrial Initiatives

By including industry partners in participatory and/or advisory activities led by academic researchers, the advanced technology developed was transferred to the private sector where larger-scale plants could be constructed and tested through pilot plant and demonstration plant stages. The university and industry communities have further advanced the results obtained in the Penn State and WVU programs to stages ready for commercial deployment. Further investments in exploring the markets for coal-based products are warranted.

One of the largest and most visible current industry initiatives is being driven by Ramaco Carbon, a subsidiary of Ramaco Coal, founded in 2011.^{cxxxv} Its main objective is to create large volume and high margin product uses for coal-based carbon by pursuing an integrated resource, technology and manufacturing based approach to new coal uses. Based in Wyoming, the company owns 1.1 billion tons of thermal coal near Sheridan, Wyoming (Brook Mine) that is under final permit review. It has obtained approval to break ground on a new Carbon Advanced Materials Center (iCAM) research park. The iCAM will house researchers from national laboratories, universities, private research groups, and strategic manufacturing partners, and will conduct applied research (bench to pilot scale) to commercialize coal-based carbon products.

Ramaco also has plans to create a 100+ acre C2P mine-mouth industrial park called Wyoming iPark. Plants in the Innovation Park (iPark) would use research from the iCAM and coal from the Brook Mine to manufacture advanced carbon products. Some of Ramaco Carbon's current research and strategic partners include the Western Research Institute, Carbon, Inc., Fluor Corporation, Oak Ridge National Laboratory, MIT- The Grossman Materials Group, the Southern Research Institute, and the DOE. Ramaco Carbon is focusing on four broad uses: coal to chemicals, coal to CF, coal to medical technology and coal to building products.^{cxxxvi}

Recent New DOE-Funded Programs

Relatively recent R&D results in the area of coal to carbon products include the use of pitch – a solvent extracted from coal – for carbon electrode production, including graphite furnace electrodes. Such a graphite furnace electrode has been tested in a commercial EAF at a U.S. mill.^{cxxxvii} Other products such as carbon foams and needle coke can also be produced from the extracted pitch.^{cxxxviii} Additionally, pitch has been used to produce CFs.^{cxxxix}

Last year, the DOE announced awards to several coal to carbon products projects under DE-FOA-0001849, including:^{cxi}

- Touchstone Research Laboratory, Ltd. – Development of new silicon carbon (SiC) foam utilizing coal feedstock that meets system performance requirements suitable for application temperatures > 1000°C, such as for concentrated solar power systems and supercritical-CO₂ turbine operations.
- Minus 100, LLC – Development of new or improved methods of manufacturing conductive ink pigments using coal as a primary feedstock at significantly lower cost than existing silver-based conductive inks.
- Semplastics EHC LLC – Development of coal core composites for low cost, lightweight, fire resistant panels and roofing materials.
- Physical Sciences, Inc. – Development of high-conductivity carbon material (HCCM) for electrochemical applications and generation of valuable byproducts such as minerals and low-emission gaseous fuels.

Very recently, DOE issued DE-FOA-0001992, “Maximizing The Coal Value Chain” to provide up to \$9.5 million for research projects aimed at maximizing the coal value chain. The FOA seeks research to develop innovative uses of domestic U.S. coal for upgraded coal-based feedstocks for power production and steel-making, and for making high-value solid products.^{cxli}

The DOE has also launched a new multi-lab collaboration, led by NETL in cooperation with other national labs, universities, and industry. The goal is to develop & demonstrate pathways for high-value materials and their use in making products.^{cxlii}

Rare Earth Elements (REEs) and Critical Minerals (CMs)

Overview

Should sufficient REE and CM concentrations be found in U.S. coal resources or mining by-products, this will create a new market for materials produced by coal mining operations. The development of coal-based extraction technologies, in pyrometallurgical operations such as roasting and calcining, can produce new market opportunities for U.S. coal products. Acid mine drainage (AMD) has also been found to contain relatively high levels of desirable heavy REEs.

The U.S. Congress has recognized the national security risks associated with being solely dependent on imports for REEs and CMs. Starting in fiscal year (FY) 2014 and again in FY15, they authorized DOE funding for the assessment and analysis of the feasibility of economically recovering REEs and CMs from coal and coal byproduct streams, such as fly ash, coal refuse, and aqueous effluents. In FY16-17, Congress authorized expansion of external agency activities to develop and test commercially-viable advanced separation technologies at proof-of-concept or pilot scale that could be deployed near term for the extraction and recovery of REEs and CMs from U.S. coal and coal byproduct sources. In FY18 Congress authorized external agency activities to continue to develop and test advanced separation technologies and to accelerate the advancement of commercially-viable technologies for the extraction and recovery of REEs and CMs from U.S. coal and coal byproduct sources.^{cxliii}

REE Research and Technology Development – Historical and Current Efforts

As follow-up to a 2017 DOE-led workshop⁴² to discuss technical developments that might improve the reach of U.S. coal products in domestic and international markets, a survey was made of the coal industry and academia. One of the most frequently cited topics for critical research needs was the production of strategic REE and CM concentrates. The production and sale of these concentrates can offset the costs associated with producing coal, and preliminary research results have shown potential for concentrating them using physical separations. These results have also shown that elements are found in specific gravities that are between those of pyrite and coal, offering opportunities to recover them from what would otherwise be refuse (minimizing process waste). Integration of physical separations with subsequent chemical extraction argues for hydrometallurgy research regarding the phase assemblages found in physical separation products.^{cxliv}

With respect to the recovery of strategic materials and CMs from coal byproducts, a significant body of work began in the 1940s, undertaken by the U.S. Bureau of Mines, focused on the potential to produce alumina feedstocks for aluminum smelters from central Pennsylvania underclays (floor rock under coal), the concern being the wartime security of the domestic aluminum production supply chain involving imported bauxite.^{cxlv} This body of work also led to the development of pressure leaching data^{cxlvi}, and process technology elements for the recovery of salable alumina from the pressure leach liquor.^{cxlvii} This type of process can render alumina-rich coal byproducts as economic feedstocks for the domestic aluminum industry. Additionally, where these byproducts contain elevated contents of strategic and critical elements, recovery of these from the leach liquor could further improve process economics.

Following recent Congressional authorizations, the DOE NETL established a REE program with a mission to develop an economically competitive and sustainable domestic supply of REE and CMs to assist in maintaining our nation's economic growth and national security. The program's objectives are to recover REEs from coal and coal byproduct streams, such as coal refuse, clay/sandstone over/under-burden materials, aqueous effluents and power generation ash. It also aims to advance existing and/or develop new, second-generation or transformational technologies to improve process systems economics and reduce the environmental impact of a coal-based REE value chain. The program's primary goal is, by 2020, to validate the technical and economic feasibility of small, domestic, pilot scale, prototype facilities as well as to generate, in an environmentally benign manner, 10 pounds per day, 1,000 pounds total, high-purity (90-99wt%), salable, rare earth oxides (REOs) from 300 part per million (ppm) coal-based resources.^{cxlviii}

The DOE NETL REE program now has over 25 active projects from a series of FOAs, covering enabling technologies, separation processes, and process systems for economically viable recovery of REEs and CMs from coal and coal byproducts. They have also formed a cooperative partnership with other national laboratories, including Los Alamos National Laboratory, Lawrence Livermore National Laboratory, and Idaho National Laboratory.^{cxlix}

Some of the most promising accomplishments/developments to date from this program include the following:^{cl}

- University of Kentucky - Produced small quantities of 80wt% total REEs on a dry basis and more than 98wt% REOs. Critical elements such as neodymium and yttrium (used in national defense technologies and the high-tech and renewable energy industries) represented more than 45% of the total REE concentrates. They also started up a pilot plant in late 2018 that is currently producing a few grams per day of a REO concentrate containing greater than 90wt% total REOs (dry basis). The products were from processing leachate collected from a coarse refuse area.
- West Virginia University - Achieved lab recovery of nearly 100% REEs from coal AMD sludge as 5-6wt% mixed REE concentrates and are now commissioning an extraction bench/pilot-scale facility for recovery of REEs from AMD feedstock.
- University of North Dakota – Identified that approximately 80% to 95% of the REE content in lignite coals is organically associated, primarily as coordination complexes as opposed to mineral forms typically found in the older/higher-rank coals.
- Physical Sciences Inc. (PSI) – In cooperation with the University of Kentucky, the University of Wyoming, and others, achieved >30wt% mixed REE pre-concentrates from coal-based materials. Built a micro-pilot facility that produced >15wt% concentrates of mixed REEs from post-combustion ash resulting from burning East Kentucky fire clay coal in a power plant boiler. PSI is now building a pilot facility in Sharon, PA to be operational by June/July 2019.
- Marshall Miller & Associates – Received a Phase I award to develop a process design and techno-economic analysis for a proposed 90-99wt% REE recovery facility (extraction and separation system) based on conventional technologies. If successful, in a subsequent Phase II down-select, they would then construct and operate a facility to produce 10 pounds per day and 1000 pounds total of a salable REE product (90-99wt% purity REOs).

- NETL – Developed a fiber optic sensor for detection of ppm levels of REEs in liquid samples. Developed immobilized amine and organo-clay sorbents for REE recovery from liquid sources. Produced 2wt% REE pre-concentrates in a lab-scale facility.

On the industrial front, Crazy Horse Coal has an automated technology for mining from deep formations that would otherwise be unrecoverable by other mining methods.^{cli} Their technology offers opportunities for the integration with coal upgrading technologies, notably those involving physical separations. They recently completed a successful proof-of-concept well project. In addition to representing a novel method for producing coal, this system may also be useful for the recovery of strategic and critical elements from geology that are too deep to mine.

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- ⁱⁱⁱ The estimated range of 300-400 million tons per year was based on direct communications with Nexant and Higman Consulting Ltd.
- ^{iv} The estimated range of 300-400 million tons per year was based on direct communications with Nexant and Higman Consulting Ltd.
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Appendices



COAL IN A NEW CARBON AGE
POWERING A WAVE OF INNOVATION IN
ADVANCED PRODUCTS & MANUFACTURING

National Coal Council Draft Report

Appendices

May 2019

The National Coal Council is a Federal Advisory Committee established under the authority of the U.S. Department of Energy. Individuals from a diverse set of backgrounds and organizations are appointed to serve on the NCC by the U.S. Secretary of Energy to provide advice and guidance on general policy matters relating to coal and the coal industry. The findings and recommendations from this report reflect a consensus of the NCC membership, but do not necessarily represent the views of each NCC member individually or their respective organizations.

APPENDIX A

Markets for Coal in the New Age of Carbon: Technology and Market Descriptions

This appendix provides a more detailed overview of the technology pathway and market descriptions. A rough outline of the main technology pathways are shown below in Figure A-1.

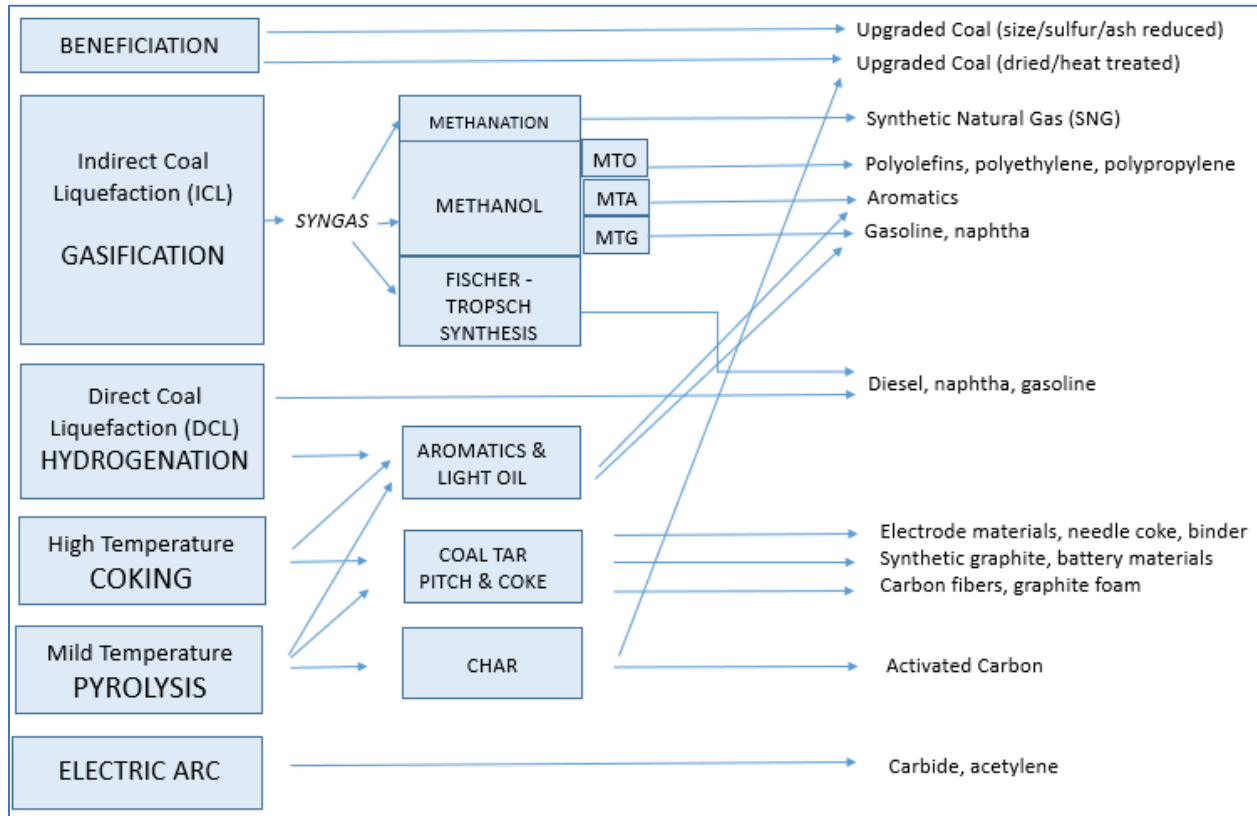


Figure Appendix A-1. Main Coal Processing Pathways

The general outline for this section is as follows:

- Coal Beneficiation
- Coal to Liquids
 - Indirect Coal Liquefaction to Chemicals (olefins, aromatics, ammonia)
 - Indirect Coal Liquefaction to Fuels (FT, MTG, SNG)
 - Direct Coal Liquefaction to Fuels (diesel, gasoline, jet fuel)
 - Direct Coal Liquefaction to Chemicals (aromatics and light oil)
 - Coal to Liquids Coking (light oils, coal tars)
 - Coal to Liquids Pyrolysis (light oils, char, coal tars)
- Coal to Carbon Products
 - Activated Carbon
 - Coal to Carbon Fiber
 - Coal to Graphite and Electrodes
 - Coal Use in Metallurgical Applications
 - Coal to Carbides
 - Coal to Graphene
 - Coal to Building Products (coal fly ash, coal combustion residuals, coal plastic composites)
 - Coal to Carbon Foam
 - Coal to Carbon Black

- Coal-derived Rare Earth Elements and other Critical Minerals
- Life Sciences and Medical
- Biotech and Agricultural Uses

Coal Beneficiation

As used in this report, coal beneficiation relates to the upgrading of coal quality. Coal quality is a significant determinant of a coal product's competitiveness, whether in domestic or international markets and whatever the application. The International Energy Agency (IEA)-affiliated IEA Clean Coal Centre published a report in 2017 which reviewed numerous beneficiation technologies, and estimated expense to be between \$2 and \$10 per ton of coal (Figure Appendix A-2).

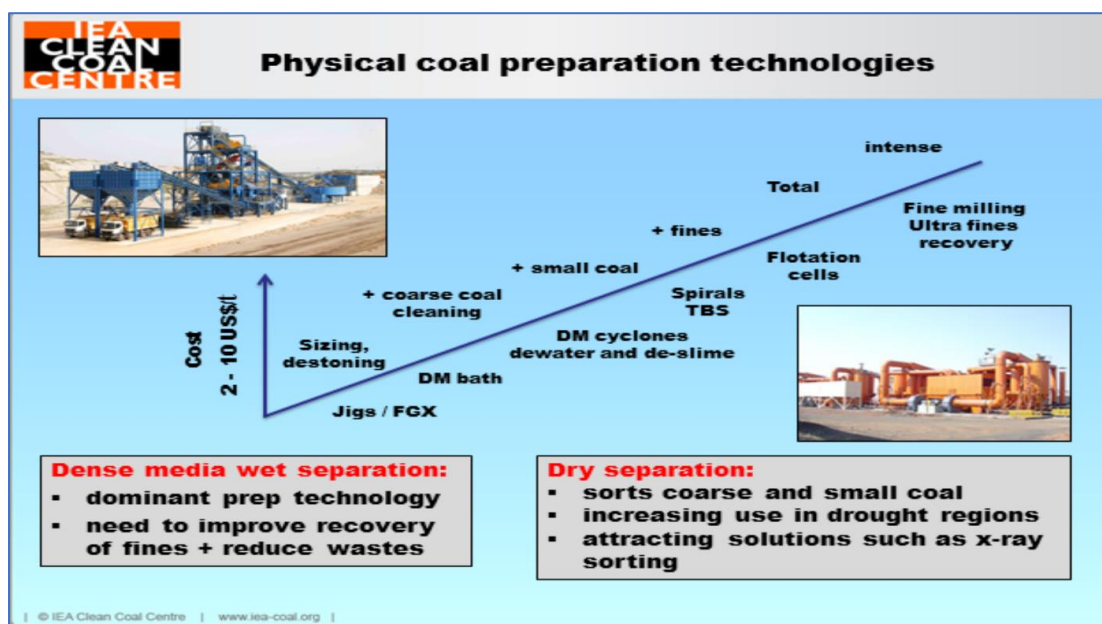


Figure Appendix A-2. Coal beneficiation methods and technologies (Reid, 2018)

This figure largely covers standard coal preparation (prep) as commonly practiced at operating coal production facilities across the globe, to improve and provide consistency in coal quality. In addition to potentially improving existing technologies, it is expected that new opportunities for expanded coal use may also result from the upper end “intense” portion of the IEA chart; i.e., higher temperature processing, finer milling and ultra-fines recovery.

Several technologies are focused on innovative applications of drying technologies and serve the added beneficiation benefits of removing unwanted impurities such as mineral matter and/or trace metals. Other beneficiating technologies are focused on upgrading coals beyond the levels typically achieved by traditional coal prep plants. Common characteristics of these technologies include (i) the use of fine coal slurry material (either from a fine coal process or waste stream, such as the thickener underflow, at a coal prep plant, or from an existing fine coal slurry refuse impoundment) as a feedstock, (ii) the production of a finished product that includes certain quality advantages – i.e., reduced ash content, reduced sulfur content, reduced moisture content, and/or increased heat content – relative to a typical washed coal product, and/or (iii) the production of a product having a fine or ultrafine size consist.

Technologies such as these have the potential to produce beneficiated coal products with sufficiently low levels of impurities – particularly ash – to be used in specialty applications such as incorporation into liquid fuels, utilization in smelting operations, or production of high-purity carbon products¹. Recent studies point toward achieving low enough levels of contamination, particularly moisture and ash as key challenges for success, which could potentially be met with micronized refined coal (MRC) beneficiation techniques^{2,3}. Moreover, to the extent that these technologies are able to utilize fine coal waste as a feedstock, they have the potential to significantly improve the environmental profile of coal mining operations by reducing the need for fine coal slurry impoundments.

Coal Quality Requirements. Coal quality requirements for non-conventional markets can differ significantly from those required for power generation applications. Coal in the latter use is a source of energy, with its calorific value being the key quality parameter. Additional quality requirements can derive from the effect of moisture and ash content on shipping costs and plant equipment, as well as the effect of volatile matter content and ash composition on plant-specific ignition characteristics and slagging and fouling behavior, respectively.

Coal quality requirements for non-conventional markets are governed by its use in equipment such as gasifiers, its use as a metallurgical reductant, and its use as a source of pitch and carbon. Example quality parameters include the following:

Ash Content

Some applications – notably use as feedstock for granular activated carbon and reductant for silicon metal smelters – can require ash contents below 2 wt%. Needle coke and anode coke for electrode applications have even lower ash content requirements, and may also have maximum levels of individual impurities, such as vanadium (V), iron (Fe) and titanium (Ti). For some gasifiers, ash in the feedstock imposes a thermodynamic penalty which can impact coal use in CTL and CTC applications. The ash content in coal products used in pyrometallurgy is also a thermodynamic penalty.

Ash Composition

In some applications requiring very low ash contents there are limits on the presence of individual impurities. Broadly, for both gasification and metallurgical applications, ash composition will govern the requirements for adding flux in order to maintain slag fluidity. In the case of fluid bed gasification systems, the ash composition and its distribution across the composite coal will influence its propensity for agglomeration, and may preclude the suitability of a given coal source for this application.

¹ <http://dels.nas.edu/resources/static-assets/besr/miscellaneous/Open-Session-Materials/CER/2018/October/Arnold,%20Barbara.pdf>

² <http://www.isamill.com/en/downloads/TechnicalPapers/Sedgman%20lecture%2010%20June%202015.pdf>

³ http://www.arq.com/docs/arq_white_paper_dec_17.pdf

Volatile Matter Content

Many applications for coal products in extractive metallurgy have requirements for volatile matter content. Coal beneficiation processes that use physical separations and thermal processing below 600°F will not significantly influence volatile matter content. However, coal across the full range of volatile matter contents is mined in the U.S., and changing the volatile content of coal could result in having the new product compete with existing U.S. mined coals.

Moisture

Moisture can be undesirable in metallurgical applications, resulting in a thermodynamic penalty and, potentially, a significant safety hazard. Coal is currently thermally dried for some metallurgical applications. Inherent moisture can also be a penalty in gasification applications for liquid fuels or chemicals, where slurry-fed gasification systems are used. Excessive inherent moisture can make it impossible to keep the gasifier feed slurry at the optimum water content. On the other hand, extracted water can be recovered for later use within a gasification plant and/or coal-to-products conversion plant.

Coal Beneficiation - Market Attributes

At the time of this writing, a large-sized coal prep plant would typically be operating at a 500~1,500 tons per hour scale. The economic viability of these projects depends heavily on cost of steel and is anticipated to provide an ROI greater than 15%.

- Probability of Technical and Commercial Success – Estimated to be $\geq 80\%$ for any new technology deployments since significant coal beneficiation plants are present and commercially successful in improving the quality of thermal and metallurgical coals. Research and development to enhance coal quality to more stringent specifications necessary for coal-derived advanced materials and products is required to adapt lower TRL technologies into existing commercially operating coal beneficiation plants.
- Cycle Time to deploy first commercial for new technology estimated to be 2~3 years
- Regulatory Attributes - Highly flexible plant operational capabilities, with minor to moderate regulatory hurdles/uncertainty, when deployed at existing commercial beneficiation plants.
 - Water: Coal beneficiation is expected to be water generating when deployed a drying mode that captures the incipient moisture released from coal
 - Air / CO₂: Air emissions are dependent on the thermal energy (heat) source employed. If coal is burned, then emissions will need to be considered and captured. For co-location with waste heat sources such a low-grade waste heat from cement or thermal power plants, then additional emissions are minor. Use of renewable electricity for heating is expected to result in near-zero air emissions.

Coal to Liquids

Coal-derived liquids first came to prominence in the 1850s, when kerosene was first distilled from coal tars for use as kerosene fuel in lanterns. These early coal-derived products ushered in the first coal liquefaction processes and the first modern industrial distillation practices. The one key advantage of converting solid carbonaceous materials, such as coal, into liquid fuels and chemicals is the improvement in ease of use – via pipeline transportation – and efficiencies in processing – in much the same way that liquids and gases are handled in the oil and gas sector today.

The key technical challenge for converting coal at high yield to liquids is coal's natural physical state, which is a highly carbonaceous solid. It is deficient in hydrogen (H_2) relative to typical petroleum-derived liquid transportation fuels.

From a technical perspective, coal liquefaction processes are viable, and hydrogen plays a key role for converting coal into desirable hydrocarbon liquids. From an economic perspective, the need for H_2 adds to processing costs. The three main liquefaction processes include:

- 1) direct coal liquefaction (DCL) process via hydrogenation/solvolytic;
- 2) indirect coal liquefaction (ICL) process via production, and subsequent chemical conversions of synthesis gas (syngas); and
- 3) thermal pyrolysis processing of coal.
 - a. the low temperature pathway is focused on liquids as the desired products
 - b. the high temperature coking pathway is focused on metallurgical coke as the desired product, with a relatively small yield of co-product liquids.

Processes that produce liquid fuels, chemicals, and synthetic natural gas (SNG) from coal can involve prior conversion of the coal to syngas (through coal gasification). Cleaned and chemically adjusted syngas is used as feedstock for chemical reactions that can produce fuels and chemicals. Among the fuels that can be produced are diesel fuel and methane (SNG). Chemicals that can be produced include methanol and ammonia (NH_3). Methanol can be used as feedstock for both chemical and fuel production such as olefins, gasoline, or dimethyl ether (DME). Ammonia, either itself or following conversion to urea, is a building block for fertilizers for agricultural markets. Urea is also used for diesel engine emission control to capture nitrous oxides (NO_x) combustion products.

Indirect Coal Liquefaction to Chemicals (Olefins, Aromatics, Ammonia). ICL to chemicals – via methanol-to-olefins (MTO), methanol-to-propylene (MTP) and methanol-to-aromatics (MTA) – is a multi-step process illustrated in Figure Appendix A-3. This begins with coal gasification to produce syngas, followed by conversion of syngas to methanol, and then followed by conversion of methanol to olefins, propylene, or aromatics. The MTO process produces ethylene and propylene while the MTP process produces propylene, and the MTA process produces aromatics such as benzene, toluene, and xylenes (BTX).

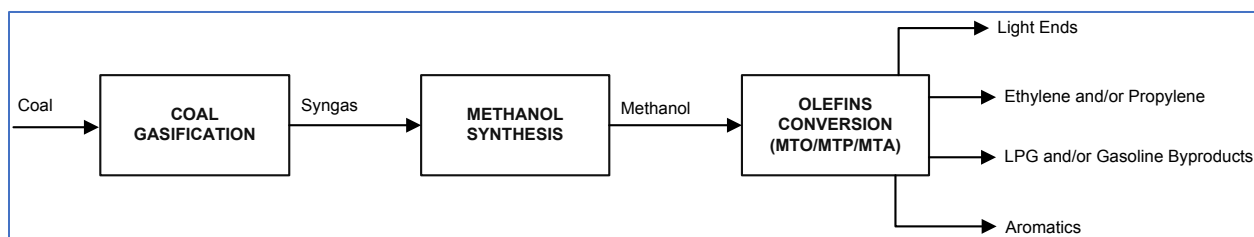


Figure Appendix A-3. Gasification-Based Coal to Chemicals Processes

The coal gasification process is a partial oxidation process. Because the gasification reaction only uses a fraction of the theoretical oxidant (air or pure oxygen) needed for complete combustion of coal to carbon dioxide (CO₂) and water, a mixture of primarily carbon monoxide (CO) and H₂ or syngas is formed. The composition of syngas can be adjusted depending on the downstream need of the gas. The major coal gasification technologies are based on fluidized bed, fixed-bed or entrained-flow processes and are available from many major technology licensors.

Methanol synthesis combines H₂ and CO to produce methanol via an exothermic reaction typically on a copper-based catalyst. The methanol synthesis process generally produces steam in a water cooled reactor that can be used in other parts of the process. Crude methanol, a mixture of methanol and water, is then typically sent to the methanol conversion process (MTO or MTA). There are seven major licensors of methanol synthesis technology and they include Air Liquide/Lurgi, Casale, Haldor Topsøe, Jacobs, Johnson Matthey, Mitsubishi, and Toyo.

MTO and MTP conversion technology can produce mixed light olefins (ethylene and propylene) or only propylene depending on the catalyst used and the technology offered. China remains the only country in the world operating MTO and MTP processes. MTO entered commercial operation in 2010 and MTP was commercialized shortly thereafter in 2011. Major licensors of MTO technology are SYN Energy, UOP, and Sinopec. Licensors of MTP technology are Air Liquide/Lurgi, and a joint venture group (Tsinghua University, China National Engineering Group Corporation (CNCEC) and Anhui Huaihua Group).

MTA technology produces a mixed aromatics stream composed of BTX. A fluidized bed MTA process was developed by Tsinghua University and Huadian Coal Industry Group. A fixed bed MTA process was developed jointly by the Shanxi Institute of Coal Chemistry.

Ammonia (NH₃) synthesis combines H₂ and nitrogen (N₂) to produce ammonia via an exothermic reaction. Ammonia is recovered by cooling and condensing liquid ammonia and serves as the key precursor for urea and other nitrogen-bearing fertilizers. Major licensors of ammonia synthesis technology include KBR, Casale, Haldor Topsøe, and thyssenkrupp.

Olefins and aromatics are the basic building blocks for most of the petrochemical industry. The commercially important olefins are ethylene and propylene, and the commercially important aromatics are benzene and para-xylene. Global consumption of ethylene, propylene, benzene, and para-xylene in 2018 is estimated to be 160 million tons, 109 million tons, 50 million tons, and 47 million tons, respectively. The primary use of ammonia is in fertilizer applications, either directly applied or as an intermediate for the production of nitrogenous fertilizers. Global consumption of ammonia in 2018 is estimated to be 179 million tons.

Indirect Coal Liquefaction to Chemicals - Market Attributes

- U.S. Competitiveness - Coal-based MTO plants for the production of olefins (ethylene and propylene) were commercialized in China, supported by government efforts to reduce the country's dependence on petroleum and petrochemical imports. While coal is also an abundant natural resource in the U.S., coal-based production of olefins is currently not competitive with conventional steam cracking processes which have lower capital intensity.

Furthermore, with the advent of shale gas in the U.S., ethane and NGL cracking have emerged as the lowest cost production route for olefins. Low cost natural gas is also the primary driver for ammonia plants in the U.S., which are based on steam reforming technology that consumes natural gas rather than gasification technologies that consume coal.

Conventional routes to benzene and para-xylene in the U.S. are based on naphtha reforming due to the large gasoline production capacity in the region. At today's relatively low oil prices, naphtha-based aromatics have more competitive production costs than coal-based MTA processes that consume large volumes of methanol per unit of aromatics produced. There are no MTA plants in operation in the U.S.

- Current Gross Market Revenue Size - Based on 2018 global consumption of ethylene, propylene, benzene, and para-xylene and assuming United States average 2018 prices, the gross revenue for these products is approximately \$330 billion. Considering ammonia will add another \$54 billion.
- Current Gross Coal Volume Size - Estimated coal consumption into olefins (ethylene and propylene) production in 2018 is approximately 25 million tons. Approximately 10 million tons is consumed in MTA plants, and 90 million tons consumed in ammonia production. All coal consumption in these applications is in China.
- Future Potential Gross Coal Volume Size - Ethylene demand is expected to grow at an annual rate of 3.6 percent between 2018 and 2028, while propylene is expected to grow at 4.2 percent annually across the same period resulting in 123 million tons per year of incremental ethylene and propylene demand. Current coal-based olefins make up about 4 percent of global olefins capacity. The potential coal consumption through 2028 based on providing 4 percent of incremental olefins demand with coal-based capacity is 15 to 20 million tons of coal.

Benzene demand is expected to grow at an annual rate of 2.7 percent between 2018 and 2028, while Para-xylene is expected to grow at 4.4 percent annually across the same period resulting in 40 million tons per year of incremental benzene and para-xylene demand. There is currently no coal-based aromatics production capacity. The potential coal consumption based on capturing 3 percent of incremental aromatics demand with coal-based capacity is 5 million tons of coal.

Ammonia demand in China is expected to grow at 2.2 percent between 2018 and 2028. Assuming all additional production is satisfied by coal-based ammonia, the additional consumption of coal is 20 to 25 million tons.

- **Required Investment Scale (Est)** - MTO, MTP, and MTA technologies all require methanol as an intermediate which should be designed with a world-scale production capacity of 5,000 tons per day of methanol (or greater) to take advantage of economies of scale. On this basis, coal consumption of the upstream gasifier will be around 6,000 tons per day. Derivatives capacity via MTO is 600,000 tons per year of olefins (ethylene and propylene), MTP is 470,000 tons per year of propylene, and MTA is 420,000 tons per year (based on para-xylene). An investment in a plant to produce the full value chain from coal to olefins or aromatics in the U.S. is between \$3.5 and \$4 billion.

Coal-based ammonia production based on large scale coal gasification plants similar in size to that which would support MTO, MTP, and MTA plants (i.e. 6,000 tons per day of coal consumption) will produce about 1.5 million tons per year of ammonia with a capital investment between \$3 and \$3.5 billion.

- **Market Conditions for Profitability** - The production of methanol or ammonia from coal is not strongly influenced by crude oil price fluctuations. As such, the cost of ammonia and the cost of producing of methanol to the derivative plant (MTO, MTP, or MTA) are relatively stable. These derivative technologies, however, produce byproducts whose prices are influenced by crude oil prices. High crude oil price will provide higher byproduct values, thus reducing the cost of production of olefins or aromatics produced by MTO, MTP, or MTA, making them more competitive at high oil prices compared to low oil prices.

In the U.S., for MTO, MTP or MTA, all three coal-based technologies will require oil prices in excess of Nexant's high oil scenario (\$90/bbl based on Brent Crude Oil) to achieve a positive return on capital. The greatest hurdle to economic viability is the high capital investment required for the multiple steps required to convert coal to olefins or aromatics.

For ammonia production using coal, which does not produce byproduct hydrocarbons influenced by oil price, cost of production based on \$13/ton (metric ton) coal from the Powder River Basin is near parity with conventional production at \$3/MMBTU natural gas. Investment cost for the coal-based ammonia plant, however, is nearly twice that of the gas-based plant.

- **Probability of Technical and Market Success** - Probability of technical success is 100 percent since ammonia, MTO, MTP, and MTA technologies are already in commercial operation. Probability of market success in the U.S. is currently very low due to the availability of lower cost (capital and production cost) alternative production routes.
- **Cycle Time to Deploy First Commercial Unit** - Ammonia, MTO, MTP, and MTA technologies are commercially available technologies. These are akin to large integrated petrochemical facilities and commercial project development time would be roughly 3-5 years.
- **Regulatory Attributes, Emissions/Water Savings** - Reuse of process water is fundamental to minimizing water consumption and discharge from the gasification, MTO or MTA process. In the gasification process, water is given a two-step treatment to remove dissolved gases (primarily acid gases) where carbon dioxide and hydrogen sulfide are removed. The majority of process water is recycled to the slurry preparation area or directly to the gasifier.

Indirect Coal Liquefaction to Fuels (FT, MTG, SNG)

Indirect coal liquefaction process can convert coal into fuels; for example, 1) into gasoline via methanol to gasoline (MTG), 2) into diesel via Fischer Tropsch (FT) conversion of syngas, 3) into synthetic natural gas (SNG) via methanation. Analogous to ICL to chemicals processes described in the previous section, these are all multi-step processes starting with coal gasification to produce synthesis gas.

Indirect Coal Liquefaction to Fuels (FT, MTG, SNG) – Market Attributes

- U.S. Competitiveness - Coal-based FT, MTG and SNG plants for the production of fuels (diesel, gasoline, methane) have been commercialized in the past 10-15 years in China, supported by government efforts to reduce the country's dependence on petroleum and natural gas imports. While coal is also an abundant natural resource in the US, coal-based production of fuels is not currently considered to be competitive with conventional petroleum refining and abundant natural gas supplies. Shale gas and shale oil in the U.S. have emerged as the lowest cost production routes for liquid transportation fuels and natural gas in the US. There is one large-scale SNG plant in operation in the USA that started up in 1984⁴ and has demonstrated the ability to produce a slate of products including synthetic natural gas (SNG), ammonia-based fertilizers and CO₂ for enhanced oil recovery. No new projects have been announced.
- Current Gross Market Revenue Size - The target markets for coal-to-fuels is vast. Based on 2018⁵ global consumption of crude oil and natural gas estimates, and assuming global average 2018 prices, the gross revenues for these two products are approximately \$2.5 trillion and \$500 billion respectively
- Current Gross Coal Volume Size - Estimated coal consumption for fuels production in 2018 was approximately 60 million tons⁶. With the exception of the Great Plains SNG plant in North Dakota and the Eastman Coal Gasification plant in Tennessee⁷ nearly all other coal consumption in these coal gasification applications are in South Africa and, most predominantly, in China.
- Future Potential Gross Coal Volume Size - Current coal-based MTG gasoline fuels make up less than an estimated one percent of global fuels capacity. Although liquid transportation fuel demand is set to grow at a modest rate between 2018 and 2028, it is not expected that ICL to fuels projects will meet added demand.

Direct Coal Liquefaction to Fuels (diesel, gasoline, jet fuel). DCL⁸ involves the solvent extraction of organic material from coal and the hydrogenation of the extracted material. Like the family of ICL processes, it can produce fuels and chemicals. Following the oil crisis of the 1970s, significant coal liquefaction R&D was undertaken in Australia, Europe, Japan and the U.S., although much of this development was subsequently put on hold as oil prices stabilized from the mid-1980s and through the 1990s. These included major coal liquefaction processes such as and illustrated in Figure Appendix A-4.

⁴ <https://www.dakotagas.com/about-us/history/1980-1986>

⁵ <https://www.statista.com/statistics/271823/daily-global-crude-oil-demand-since-2006/>

⁶ Estimates by this report

⁷ https://en.wikipedia.org/wiki/Eastman_Chemical_Company

⁸ Burke, F. P., Brandes, S. D., McCoy, D. C., Winschel, R. A., Gray, D. and Tomlinson, G., "Summary Report of the DOE Direct Liquefaction Process Development Campaign of the Late Twentieth Century: Topical Report" July 2001, DOE Contract DE-AC22-94PC93054.

<ul style="list-style-type: none"> • Exxon Donor Solvent (Exxon, USA) • H-Coal (HRI, USA) • NEDOL (NEDO, Japan) 	<ul style="list-style-type: none"> • Solvent Refined Coal (SRC-I/II) (Gulf Oil, USA) • Kohleol (Ruhrkohle, Germany)
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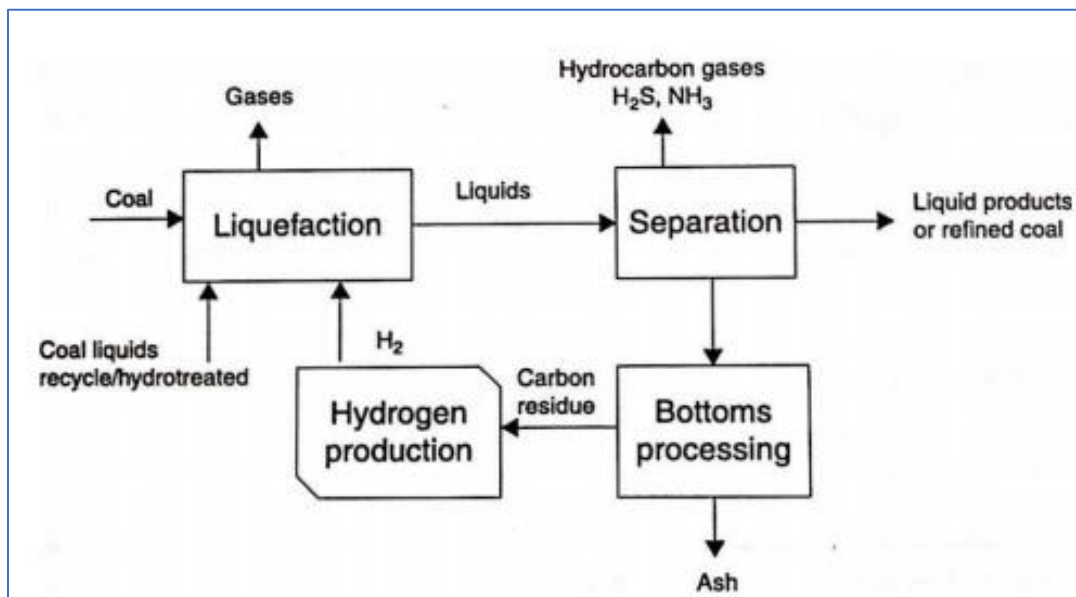


Figure Appendix A-4. Typical Direct Coal Liquefaction process⁹

DCL processes are fully developed and commercially utilized technology today in China, but have not yet been deployed at a commercial scale in the U.S. Coal conversion to liquids fuels provides a market opportunity to utilize U.S. coal resources to reduce and/or eliminate the net import balance of crude oil and petroleum products, produce strategic domestic fuels for national security and create new employment opportunities in economically distressed coal producing regions of the U.S.

Additionally, DCL creates synergistic opportunities with U.S. natural gas, by using the H₂ in CH₄ required for the DCL process. The synergies are especially evident in the Appalachian coal seams that overlay Marcellus shale gas production, and other regions where coal and natural gas are found nearby.

DCL can process a wide range of U.S. coal resources including bituminous, sub-bituminous and lignite. The liquid fuel yields are in the range of 4.0-4.5 barrels of oil per ton of bituminous coals and 3.5-4.0 barrels per ton for sub-bituminous coals and lignite. A DCL facility is very much the same as a petroleum refinery, refining coal instead of crude petroleum oil. The core conversion DCL process technology is a derivative of processes used in refineries for decades. After the coal is converted to liquid, the processing facility is identical to a petroleum refinery, with distillation processing to separate the fuel products and conventional refining processes to produce clean liquid fuels that meet U.S. EPA fuel standards for gasoline and ultra-low-sulfur diesel.

⁹ Khan, M. R. (Ed.).(2011). Advances in clean hydrocarbon fuel processing: science and technology. Woodhead Publishing Series in Energy, 15-29.

Direct Coal Liquefaction to Fuels (diesel, gasoline, jet fuel) – Market Attributes

- U.S. Competitiveness – Vast coal resources and abundant low-cost natural gas. For DCL coal-to-liquids, this provides significant synergy, with the ability to produce low-cost hydrogen for the hydrogenation requirements of DCL.
- Required Investment Scale (est.) - The investment cost for a minimum sized commercial DCL facility with a production capacity of 10,000 BPD of liquid fuels (from 2,500 TPD of coal) is around \$1 billion. A maximum sized single DCL train can process about 8,000-10,000 TPD of coal producing about 32,000-40,000 BPD of liquid fuels. The economic viability of these projects depends on the price of oil.
- Market Conditions for Profitability (est.) - The minimum price of oil required for a profitable DCL facility is in the range of \$50-60/bbl.
- Probability of Technical and Commercial Success - Low or no technical risk based on DCL commercialization outside of the US. Market success is dependent on sustained oil price above \$50-60/bbl.
- Cycle Time to deploy commercial project - Commercial project development time is 3-5 years.
- Operational viability, regulatory hurdles/uncertainty: Highly flexible plant operational capabilities with minor to moderate regulatory hurdles/uncertainty when deployed at existing commercial facilities.
- Water: Requirements are similar to existing petroleum refineries. Modern designs maximize water recovery and re-use in the facility. Main make-up water requirement is for evaporative losses of cooling water, which are minimized by maximum heat recovery and air cooling.
- Air/CO₂: DCL facility air emissions are within all state and U.S. EPA minor source requirements for permitting. The main source of CO₂ emissions from a DCL facility is from the hydrogen-producing unit and existing technologies are available for CO₂ capture.
- End-use products meet all U.S. EPA standards for gasoline (Tier 3) and diesel (ultra-low-sulfur).

Direct Coal Liquefaction to Chemicals. DCL is particularly well suited to the co-production of certain chemicals¹⁰. This is due to the fundamental chemical structure of coal. Coal has a very complex structure but within that structure are aromatic compounds (BTX isomers) that are high volume (about 100 MTPY) chemical commodities, used to produce plastics products and synthetic fibers. Since DCL involves the direct conversion of CTL, it is able to remove and retain the aromatic compounds from the coal. Once the coal is converted to liquid, conventional oil refining technologies can be used to produce high yields of high purity BTX chemicals.

¹⁰ 10 Burke, F. P., Brandes, S. D., McCoy, D. C., Winschel, R. A., Gray, D. and Tomlinson, G., "Summary Report of the DOE Direct Liquefaction Process Development Campaign of the Late Twentieth Century: Topical Report" July 2001, DOE Contract DE-AC22-94PC93054.

Today, most of the BTX is derived from petroleum. A small amount (< 5%) is coal-derived from coke oven light oils, mainly in China. The U.S. is a net importer of benzene and net exporter of xylenes. The importance and value of these chemical commodities is reflected by a growing trend in the oil refining industry today: Crude Oil to Chemicals (COTC). There are several announced COTC projects worldwide. Figure Appendix A-5 illustrates one such project in China.

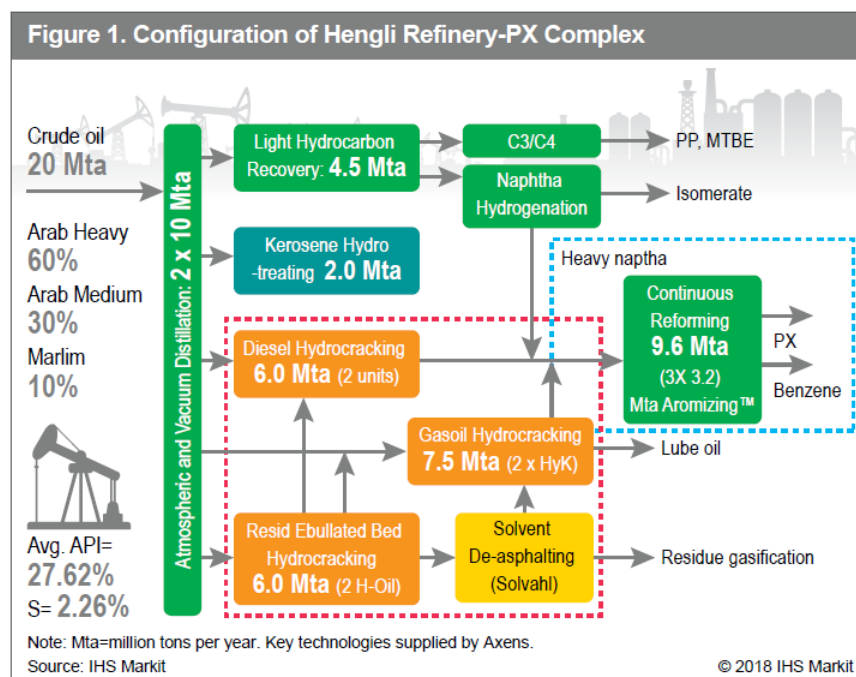


Figure Appendix A-5. Typical Configuration for Crude Oil to Chemicals (Naphtha Aromatics)

(Note this figure is copyrighted by IHS Markit¹¹)

Direct Coal Liquefaction to Chemicals – Market Attributes

- Configuration above outlines the possibility to produce 4-16 Million tons per year of benzene, toluene and xylenes (BTX) from coal, when coal is substituted as feed stock for crude oil. This BTX can be refined to produce high purity benzene and paraxylene (PX) which are the largest volume commodities in the BTX family of aromatic chemicals, and highest value.
- The major impact is on the investment cost for and revenue from the DCL facility. The investment cost is increased by 15% for the DCL facility. As high value chemical commodities are produced the revenue is increased by 30%.
- In terms of profitability compared to crude oil pricing, production of chemicals from coal can reduce this by about \$10/barrel compared to fuels production, or about \$40-50/barrel.

¹¹ Johnson, D. and Chang, R.J., "Crude oil-to-chemicals projects presage a new era in global petrochemical industry," Posted 06 August 2018 by IHS Markit , <https://ihsmarkit.com/research-analysis/crudeoil-chemicals-projects.html>

Coal to Liquids Coking (light oils, coal tars). Coal tar and coal tar pitch are produced as byproducts of high temperature (1000°C) coke-making. In the early 20th century, large quantities of light oils and coal tars were used as feedstocks for other industrially important chemicals including wood preservatives, synthetic dyes, explosives and early plastics. They have had many uses industrially, including in consumer products, and were largely displaced by petroleum-derived substitutes in the mid-20th century. Coal tar pitch products, which are distillate products of coal tar, are used today primarily as binders for aluminum smelting electrodes, in roofing materials, surface coatings and pavement sealants.

In the U.S. the availability of coal-derived tars and light oils has steadily decreased, due to the off-shoring trend of the steel making industry, together with a trend toward new means of steel production via ‘mini mills’ which do not require as much coke. Additionally, there’s been a trend toward non-recovery coking operations, whereby coke-oven byproducts are consumed as fuels to supply heat for the coking operation versus recovery for their chemical product value.

The fate of this route for coal products expansion is tied closely to fate of the metallurgical coking industry, and because the co-product amounts of coal tar are relatively low (3~4% yield), we would not expect to see new coking facilities built solely on the economics of the coal tar value alone. Instead we could envision the development of on-purpose coal tar production.

Coal to Liquids Pyrolysis (light oils, char, coal tars) – Coal-derived tars can also be produced via mild-temperature (500°C) pyrolysis of coal. One such process, developed with DOE support in the 1990s, was known as the Encoal Process^{12,13,14}. The main focus of the Encoal work was on the production of a boiler-compatible char fuel and refinery compatible liquids. During the 2000s, additional work^{15, 16} focused on characterization, and upgrading of the liquids.

Although the Encoal work did not lead to commercialization in the U.S., a sizeable coal-based mild-temperature pyrolysis industry has emerged in China in recent years to produce liquids to be used mostly as blend stocks in transportation fuels and coal char or semi-coke to be used as blend stock in metallurgical operations. It was estimated¹⁷ that 4 million metric tons per year (MMTPY) of low-temperature pyrolysis coal tar is produced annually in China. One of the leading producers is the Shenhua Company, which has commercialized its CoalRef® suite of process technologies^{18, 19}.

¹² DOE/ME/27339-4088; The ENCOAL® Project Initial Commencement Shipments and Utilization of both Solid and Liquid Products, ENCOAL CORPORATION, March 1995

¹³ DOE/FE-0409; ENCOAL® MILD COAL GASIFICATION PROJECT - PROJECT PERFORMANCE SUMMARY; ENCOAL CORPORATION, CLEAN COAL TECHNOLOGY DEMONSTRATION PROGRAM, November 1999

¹⁴ DOE/NETL-2002/1171; The ENCOAL® Mild Coal Gasification Project: A DOE Assessment; U.S. Department of Energy, National Energy Technology Laboratory, March 2002

¹⁵ E. R. Skov, D. C. England, J. C. Henneforth and F. G. Rinker; Syncrude and Syncoal Production by Mild-Temperature Pyrolysis Processing of Low-Rank Coals; AIChE Spring National Meeting, Houston, Texas, April 2007

¹⁶ E. R. Skov, D. C. England, F. G. Rinker and R. J. Walty; Coal-Tar Chemicals and Syncrude Oil Production from Low-Rank Coals Using Mild-Temperature Pyrolysis; AIChE Spring National Meeting, Houston, Texas, April 2007

¹⁷ Estimate based on total amount (20 million tons) in China <https://www.globenewswire.com/news-release/2019/02/26/1742153/0/en/China-Coal-Tar-Industry-Report-2019-2025.html>, less the amount (16 million tons) attributed to metallurgical coking <https://www.itaorg.com/conference-pdfs/presentation08-day1-Zhang.pdf>

¹⁸ Clean Coal Applications...NICE Perspectives; Chang Wei, National Institute of Clean and Low Carbon Energy (NICE), Shenhua Group, 02 February 2015 <https://slideplayer.com/slide/6282071/>

¹⁹ http://www.nicenergy.com/en/html/RD_field/focusfield/

Coal to Liquids Pyrolysis (light oils, char, coal tars) – Market Attributes

- U.S. Competitiveness – China has invested significant resources into low temperature pyrolysis with a first to market vs other countries, apparently building upon the Encoal base technology from U.S.
- Current Market Size – estimated 4 million tons of coal / year
- Future Potential Gross Coal Vol Size – This is considered to be a mixed opportunity, on the one hand there would appear to be growing market for specialty coal tar pitches, but on the other hand the coal char coproduct (>75%) may grow at a more metered pace.
- Required Investment Scale (est.) - Expected to be less capital intensive than traditional coal liquefaction (ICL and DCL) processes because the operating pressures are not elevated and there is no need for hydrogen co-feed.
- Market Conditions for Profitability(est.) - Based on the current State-of-the-Art, coal pyrolysis is competitive with petroleum at approximately \$50/bbl
- Probability of Technical and Commercial Success - Technology is currently being practiced in China and other countries. However, to penetrate the U.S. market, the current state of the art would need to be improved by increasing yields or modularization to reduce capital cost.
- Cycle Time to deploy first commercial - 2 to 5 years
- Regulatory Attributes:
 - Water – the process is net positive water.
 - Emissions – depending on site conditions, plants could be near zero emissions.
 - End-use products would improve U.S. energy security and competitiveness.

Coal to Carbon Products

Carbon materials have many general properties which makes them attractive in various applications. Conventional carbon materials include graphite, carbon black and activated carbon materials. New carbon materials with tailored properties have recently been developed, including carbon fibers (CFs), highly oriented graphite and many others. Most recently, even more sophisticated nano-sized or nano-structured carbon materials such as graphene have been produced. All can be produced from coal, and in many cases, coal is a preferred precursor due to its high carbon content.

These coal-derived products serve in a diverse set of end-use applications covering aerospace, defense, automotive, environmental, agricultural, industrial electrodes, battery storage and others, building products and others. All are mainly in specialty applications with high performance criteria, such as exceptionally high durability, strength, electrical conductivity, thermal conductivity, corrosion resistance and light weight properties. These materials are often used in their pure form, and emerging as key components in mixed material composites, in alloying, and as additives in commodity materials such as concrete and asphalt used in construction and transportation sectors.

Graphene is one of the newest materials joining the ranks as a coal to carbon product, as an actively researched focus area. It is being considered as a new material in many of the sectors mentioned above and specialty applications in the field of medicine. These and other related coal-to-carbon product summaries have been reported in recent years by the UK-based IEA Clean Coal Centre ^{20,21}, which is supported by the IEA.

The focus on coal-to-products (C2P) initiatives is not entirely new. With DOE support, roughly 25 years ago, the CPCPC²² was formed to research new C2P initiatives, especially in the field of advanced carbon materials. The consortium was established with West Virginia University (WVU) as its charter member, DOE providing base funding, and Pennsylvania State University (Penn State) managing the academic-industrial partnership.

The consortium's activities included collaboration with both the coal production and carbon manufacturing industries, as well as the DOE and other academic institutions. In addition to producing research results relevant to the use of coal for producing carbon products, the consortium also helped produce a pool of graduates with the required skill sets to work in the carbon industry.

The consortium generated a body of research results which are relevant to the production of carbon products from coal.

<ul style="list-style-type: none"> • Activated Carbons • Adsorbents for Flue Gas Cleaning • Anode Coke • Carbon Electrodes for Batteries and Fuel Cells • Carbon Fibers • Carbon Foams • Carbon Nanotubes • Catalysts 	<ul style="list-style-type: none"> • Coatings for Solar Collectors • Graphites • Microporous Carbons for Hydrogen Storage • Nanofiber Sheets • Nanoporous Carbons for Ultracapacitors • Needle Coke • Pitches, Including Mesophase Pitches • Solvent Extraction Products
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Table Appendix A-1. CPCPC Research & Development focus topics

The consortium also provided market size estimates for leading coal-to-product opportunities in the 2011 timeframe, for pitch, anode coke, needle coke, carbon black, carbon fiber and others.

Activated Carbon

Activated carbon is a form of carbon generated via thermal or chemical processing of a carbonaceous feedstock such as coal (also wood and coconut shells), resulting in a porous material with high surface area. Its key forms include granular, powdered, extruded and fiber. Applications include purification of liquids and gases, from water treatment to in-duct removal of toxic compounds in gases and power plant exhaust emissions and to filtration media for breathing masks.

²⁰ Non-Fuel Uses of Coal, Herminé Nalbandian, IEA CCC Ref: CCC/236 ISBN 978-92-9029-556-3; IEA Clean Coal Centre, May 2014

²¹ Non-Energy Uses of Coal, Ian Reid, IEA CCC Ref: CCC/291 ISBN 978-92-9029-614-0; IEA Clean Coal Centre, Nov 2018

²² Enhanced Hydrogen Economics via Coproduction of Fuels and Carbon Products DE-FC26-06NT42761; Final Report Period of Performance, 1 Apr 2006 - March 31 2011; 11 October 2011 Sponsored by: U.S. Department of Energy National Energy Technology Laboratory

Activated carbon has many applications, driven by both health and environmental considerations. There are well-developed markets and technologies for the current applications, with many different products designed for specific uses. Feedstocks for activated carbons vary, and can include raw or beneficiated coal depending on the product characteristics required. Potential expansion areas are described in this section. The IEA Clean Coal Centre²³ has stated activated carbon costs range by a factor of ten, from about \$0.23 to \$2.30/lb. New activated carbon products and applications will likely be within this range.

Activated Carbon – Market Attributes

- U.S. Competitiveness – Activated carbon could be developed as a First-to-market vs other countries in terms of its potential use as a regenerable sorbent for carbon capture, utilization, storage (CCUS). Activated carbon serves as important health, safety and environmental products due to its use in air purification and water purification
- Current Gross Market Rev Size (Target Market) - The current global market for activated carbon is estimated at \$2.8 billion, with growth to over \$6 billion by 2025.
- Current Gross Coal Vol Size - Current domestic use of activated carbon approaches the equivalent of 1.3 million tons of coal. Translating this to global use suggests potential of about 5.7 million tons of coal worldwide. Assuming half of activated carbon is produced from non-coal feedstocks, the total current coal usage is estimated at 2.8 million tons.
- Future Potential Gross Coal Vol Size - Various new markets, detailed below, provide expansion potential.
- Required Investment Scale (est.) - The incremental investment to make differentiated products is small compared to that in the overall production facilities, which are currently under-utilized. The appropriate developmental investments could result in products designed to address key new markets. Relatively small investment levels (on the order of \$1 million or less) can result in a high probability of success for new activated carbons.
- Cycle Time to Deploy - The target new markets discussed below vary in their implementation timeframe. While use of activated carbon for disinfectant byproduct control (DBP) applications is needed now, there is also market growth described. An area of tremendous potential growth that is farther out in time is deployment of activated carbon as solid sorbents for CO₂ control (CCUS).
- Regulatory Attributes - The use of activated carbon is heavily driven by regulations. From air toxics control to water standards, improving health and the environment is often the primary goal. Purification is needed in many forms in industrial processes, and product quality is also a driver in pharmaceutical and other uses. Manufacturing of activated carbon from coal can be accomplished with a small environmental footprint, and BACT standards in the U.S. dictate stringent emissions levels. At least one major manufacturer also recovers the process heat for power generation on-site, offsetting CO₂ emissions significantly.

²³ Non-Energy Uses of Coal, Ian Reid, IEA CCC Ref: CCC/291 ISBN 978–92–9029–614-0; IEA Clean Coal Centre, Nov 2018

- Growth Areas - Domestic growth opportunities for activated carbon include developing new applications, driven in part by regulations such as disinfectant byproducts or utilization in new applications such as solid sorbents for CO₂ control. Water treatment in industrializing countries represents a larger long-term potential market. Other opportunities for market growth include the fracking industry²⁴ and soil remediation²⁵.²⁶ See Figure A-6 below for overall N. America growth projections.

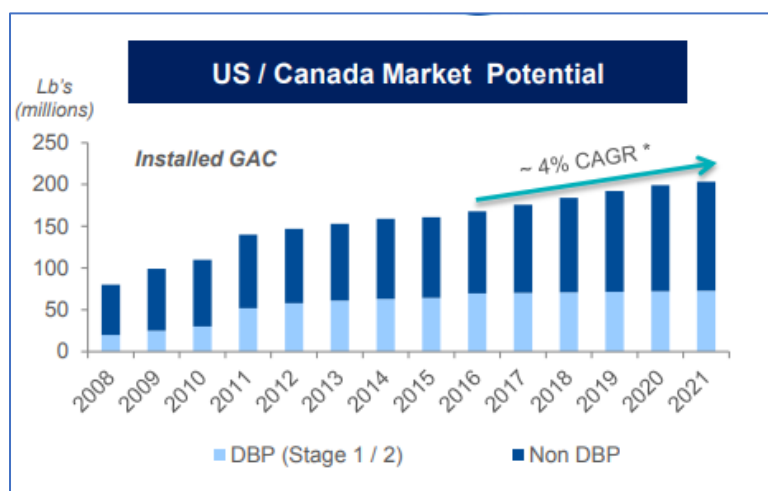


Figure Appendix A-6. North American Activated Carbon Growth Projections
(Note this figure is copyrighted by Calgon²⁷)

Additional markets are described by IHS in their Chemical Economics Handbook²⁸. Gas stream applications are expected to continue to grow, such as removal of H₂S from biogas streams as applied to landfills, anaerobic digesters, and wastewater treatment plants. A new emerging use for activated carbon is in capacitors and batteries for energy applications (e.g., batteries used in hybrid vehicles). Although the energy field is a long-term application, this could be a significant market for activated carbon in the future. Similar to the significant recent growth in demand spurred by the implementation of the Mercury and Air Toxics Standards (MATS) in the U.S., and specialty products developed to meet that demand, the Minamata convention is continuing to be implemented around the world, driving further utilization of activated carbon.

A new application yet to be fully realized is the potential for carbon capture. The IEA Clean Coal Centre²⁹ reports that removal at higher temperatures than amine solvent-based systems can allow highly efficient adsorption of CO₂ from syngas (pre combustion) streams. This work is in the trial stage.

²⁴ <https://www.mordorintelligence.com/industry-reports/united-states-activated-carbon-market>

²⁵ <https://www.futurity.org/activated-carbon-polluted-soil-1567692/>

²⁶ <https://www.epa.gov/sites/production/files/2018-04/documents/100001159.pdf>

²⁷ [http://phx.corporate-](http://phx.corporate-ir.net/External.File?item=UGFyZW50SUQ9NjYyODk2fENoaWxkSUQ9MzcwMDgxfrFR5cGU9MQ==&t=1)

[ir.net/External.File?item=UGFyZW50SUQ9NjYyODk2fENoaWxkSUQ9MzcwMDgxfrFR5cGU9MQ==&t=1](http://phx.corporate-ir.net/External.File?item=UGFyZW50SUQ9NjYyODk2fENoaWxkSUQ9MzcwMDgxfrFR5cGU9MQ==&t=1)

²⁸ <https://ihsmarkit.com/products/activated-carbon-chemical-economics-handbook.html>

²⁹ Non-Energy Uses of Coal, Ian Reid, IEA CCC Ref: CCC/291 ISBN 978-92-9029-614-0; IEA Clean Coal Centre, Nov 2018

Coal to Carbon Fiber

Carbon fibers are fibers about 5-10 micrometers in diameter, composed mostly of carbon atoms. Carbon fibers have several advantages including high stiffness, high tensile strength, low weight, high chemical resistance, high temperature tolerance and low thermal expansion. These properties have made carbon fiber very popular in aerospace, civil engineering, military, and motorsports, along with other competition sports. However, they are relatively expensive when compared with similar fibers, such as glass fibers or plastic fibers.

Carbon fibers are usually combined with other materials to form a composite. When impregnated with a plastic resin and baked, it forms carbon-fiber-reinforced polymer (CFRP) which has a very high strength-to-weight ratio, and is extremely rigid although somewhat brittle. Carbon fibers are also composited with other materials, such as graphite, to form reinforced carbon-carbon composites, which have a very high heat tolerance. Currently, 90% of carbon fiber is produced from petroleum-derived polyacrylonitrile (PAN) and less than 5% of carbon fiber worldwide is currently produced from petroleum and coal-tar pitch.

The graphitic pitch-based carbon fibers, however, have the most commercially desirable properties, being distinguished by high mechanical stiffness (high modulus), high heat and electric conductivity, zero coefficient of thermal expansion, and high dimensional stability. The use of these high and ultra-high modulus (HM/UHM) pitch-derived carbon fibers can improve the efficiency of electronics, energy storage solutions, and industrial processes across the board, and enable and support adoption of new construction and energy technologies. The use of pitch-based carbon fiber, however, is currently limited to the most demanding applications in aerospace, defense, and high-end sports equipment industries, because of its high cost of production. Market prices exceed \$80/kg – 4-5 times more costly than regular PAN-based carbon fiber, but emerging new technologies may reduce the costs below those of incumbent PAN-based fibers.

Coal to Carbon Fiber – Market Attributes

- U.S. Competitiveness - Carbon fiber is a strategic material, indispensable to the United States' security and competitiveness in the global arena. The total aerospace and defense market volume of carbon fibers in 2018 was an estimated 15,500 tons (i.e. ~40% of total U.S. carbon fiber consumption). Fast growing applications are in infrastructure, energy, and transportation for the purposes of reducing the use of energy-intensive, and heavy materials, such as steel and concrete. Other fast growing applications include in the advanced hydrogen economy, improving the efficiency of automobiles, and lowering the costs of distributed renewable wind energy generation.
- Current Gross Market Rev Size - The global carbon fiber market estimates:
 - 2016 \$1.96 billion; 2016-2022 CAGR: 11%; 2018 tonnage: ~78,500 tonnes (est)

- Primary Growth Opportunities:
 - Carbon fiber for automotive use:
 - Transportation sector is responsible for 27% of the nation's carbon emissions, 29% of total energy consumption, and 70% of petroleum consumption.
 - Reducing the weight of vehicles will significantly reduce reliance on imported energy and vehicle-related pollution. Carbon fiber has the highest weight reduction potential, as it is 50% lighter than steel with same strength and stiffness
 - Carbon fiber use in the automotive industry is currently hindered by the high cost (570% the cost of steel today)
 - Present global market: \$250 million
 - Projected global market by 2028: \$3 billion (if only 1% of the luxury car segment were carbon fiber)
 - Carbon fiber in construction / infrastructure:
 - UHM (coal-derived carbon fibers) widely used in Japan for seismic reinforcement and repair of concrete structures
 - Piloted in the United States for non-disruptive reinforcement of concrete overpasses.
 - Reinforcement of steel beams is another high impact application
 - Non-corrosive cost-effective carbon laminate reinforcement eliminates costly capital repairs or bridge replacement.
 - Benefits include, the reduction in the use of steel and concrete for new construction, and enables long term non-intrusive repairs in reinforcement projects.
 - 2018 use (United States): 17,500 tons; 2018-2023 CAGR%: 10.4%
 - Carbon fiber in energy:
 - Higher stiffness and lower mass are crucial parameters for wind turbine blades exceeding 40 m in length. Use of carbon fiber allows blades to reach lengths of 100 m, increasing generation efficiency and allowing more wind energy to be harvested per generator
 - Other energy applications include:
 - Cryogenic pressure vessels for transportation of hydrogen, LNG and other industrial gases and fuels;
 - Efficient, temperature-resistant heat conductors for solar concentrators,
 - High-conductivity and high-purity electrodes for energy storage solutions,
 - Corrosion-resistant, chemically inert heat exchangers and conduits for various energy and chemical processes.
 - 2018 use (United States): 10,400 tons; 2018-2023 CAGR%: 11.8%

- Current Gross Coal Vol Size - Coal tar, a by-product of metallurgical coal coking, is used to make carbon by only two companies (Nippon Steel and Mitsubishi) who produce coal-derived ultra high modulus (UHM) carbon fiber.
 - UHM fibers are 4-5 times more costly than regular carbon fiber, and are estimated to account for ~5% of the total carbon fiber market; translating into an annual production of 1,100 tons
 - For high-temperature metallurgical coking, yield of coal tar pitch is roughly 50 lbs per ton of feed coal,
 - Gross coal requirement to produce 1,100 tons of coal-derived carbon fiber can be estimated at 0.15 million tons today, this estimate is based on using relatively low coal tar yields (4%) from metallurgical coking operations; if instead, new on-purpose pitch production facilities could be built with order of magnitude higher yields (25%~50%) then this would reduce requisite coal feeds proportionally, same logic prevails throughout this section.
- Future Potential Gross Coal Vol Size - Projected global demand for carbon fiber is expected to exceed 260 thousand metric tons by 2025
 - If all this demand was satisfied in its entirety with coal-derived carbon fiber, then this demand would correspond to 38.2 million tons of coal / year assuming coking ovens as the source of coal tar pitch, or a factor of ten less, if assuming commercialization of higher-yielding emerging technologies.
 - Note that achievement of 100% market share is not possible in practice and simply used here as a basis for sizing the market opportunity.
- Required Investment Scale - A spinning plant with nominal capacity of 500 tons of graphitic pitch-based carbon fiber may have a total estimated CAPEX range of \$50M and \$100M USD.
- Market Conditions for Profitability - N/A: Carbon material prices are disconnected from the oil prices. Price of feedstock (coal tar pitch) may be partially correlated to the oil price at high oil prices, but for the high-margin carbon products, the feedstock price is negligible.
- Probability of Technology and Market Success - Both the carbon fiber process and the carbon fiber markets exist and are commercially proven. The markets are growing, and can be further spurred with improvements in processes and technologies that would lower costs of feedstock and processing.
- Cycle Time to Deploy First Commercial Applications - Technologies and processes are available now and are in commercial operation in Japan (Nippon Steel, Mitsubishi) and, utilizing analogous petroleum pitch feedstock, in the United States. A new 500 ton/year spinning plant could be deployed in 24 months.

- Regulatory Attributes and Emissions/Water Savings
 - Yield losses due to volatilization occur during spinning and high temperature treatment steps (carbonization and graphitization) processes, these are considerably less when processing coal-based fibers than for PAN-based fibers; both processes retain the requisite compliant emission control devices. SO_x, NO_x and fugitive emissions of VOCs and PAHs need to be addressed in new plant construction.
 - Carbonization and graphitization are high temperature energy intensive processes.
 - Lightweight, advanced carbon materials such as carbon fibers have been identified by the Department's Office of Energy Efficiency and Renewable Energy (EERE) to improve vehicle efficiency by reducing weight, resulting in considerably lower emissions. In addition, carbon fibers are being used to improve building energy efficiency and to strengthen fiber reinforced concrete, which enables the use of less cement and results in lower CO₂ emissions attributable to cement production.

Coal to Graphite and Electrodes

Graphite is a naturally-occurring form of crystalline carbon. It is extremely soft, cleaves with very light pressure, and has a very low specific gravity. In contrast, it is extremely heat resistant and nearly inert in contact with almost any other material. These extreme properties give it a wide range of uses in metallurgy and manufacturing. Graphite is used in pencils, lubricants, crucibles, foundry facings, polishes, arc lamps, batteries, brushes for electric motors, and cores of nuclear reactors, and is on the list of strategic materials.

Graphite's electrical conductivity properties are ushering in a large new market in the field of energy storage applications, which is growing rapidly thanks to ubiquitous consumer electronics and the growing market share of electric vehicles and intermittent (renewable) power generation.

Naturally occurring graphite (mined extensively in China, India, Brazil, North Korea, and Canada) has significant impurity and ash contents (> 5%) and therefore must be purified extensively for the most demanding applications. Extensive processing raises its final price by a factor of 15-20 and makes synthetic graphite a competitive and attractive alternative, especially for demanding energy storage applications.

Synthetic graphite is a man-made substance manufactured by the high temperature processing of amorphous carbon materials. Many types of amorphous carbon are used as precursors to graphite, and can be derived from petroleum, coal, or natural and synthetic organic materials.

The main markets are for carbon electrodes including 1) electric arc furnace (EAF) electrodes in the steel, ferroalloy, and silicon metal industries, 2) carbon anodes in Aluminum smelting operations, 3) and as anodes for lithium-ion batteries. In the case of the EAF electrodes for steel industry, these are graphite electrodes. In the other applications, electrodes may not be graphitized which is an important distinction as the graphitization properties of the coal-derived carbon feedstocks can be less important and thereby potentially increase markets for coal products.

Two feedstocks common to the production of these electrode products include “binder” and “aggregate” or “filler.” Binders are pitches, produced from either coal tar (recovered from coke production) or petroleum products. Aggregates are typically solid carbons, derived from coal or petroleum, depending on the material requirements. In addition to pitch, cokes for use as aggregate can be derived from coal (pitch is the intermediate), or coal itself. In the latter case, calcined anthracite is used as aggregate for cathodes for aluminum smelters, and for electrodes for ferroalloy and silicon metal production. Anodes for aluminum smelters require a very low ash content to maintain product purity, and anode coke for aluminum production is typically produced from low ash content petroleum products.

Anodes for aluminum reduction furnaces are produced from anode coke, which requires a very low ash content, and pitch, with the anodes being consumed in the smelting process. Anode cokes are produced from petroleum products.

Graphite (EAF) electrodes for the steel industry require high conductivity and resistance to chemical attack in the furnace environment and then graphitized. This requires the use of needle coke as the aggregate which commands a significant price premium over other carbon feedstocks. Other synthetic graphite products such as anodes for batteries can share these feedstock requirements.

Coal to Graphite and Electrodes – Market Attributes

- U.S. Competitiveness - Graphite is a strategic material as classified by the Defense Logistics Agency. Graphite supports core industries such as aluminum smelting (cathodes) and EAF steelmaking (electrodes), and a number of advanced and emerging technology industries, such as: nuclear, space, electric vehicles and energy storage.
 - China dominates both natural and synthetic battery-grade graphite supply lines
 - Abundant coal resources and low energy costs give a natural advantage to the United States in the energy-intensive production of this important, strategic material
- Current Gross Market Rev Size - The global graphite market estimates:
 - \$12.5 billion in 2016, projected to be \$18.2 billion in 2021
 - CAGR of 7.7% from 2016 through 2021.
- Top Applications:
 - Industrial electrodes (EAF) for steel production result in a consumption ratio of about 1 and 3 kgs of graphite per ton of steel produced, resulting in an estimated global demand of 750,000 tons of per year.
 - Lithium-ion batteries for automotive and other applications typically contain about 1 kg of graphite per kWh of battery capacity. A single Tesla battery pack is estimated to contain as much as 85 kg of graphite. Current graphite demand for the electric vehicle market is roughly 30,000 tons per year, projected to reach 40,000 tons per year by 2020.
 - Non-graphitic carbon anodes for Aluminum production result in consumption ratio of about 0.40 and 0.45 kg non-graphitic carbon consumption per 1 kilogram of Aluminum produced. Roughly 60 million tons of primary aluminum was produced in 2018.

- If 15% of these anodes are derived from coal tar pitch, then
 - 2015 demand: 5 million ton/year
 - 2020 projected demand: 6.2 million ton/year
 - If 65% is from calcined petroleum coke (with opportunity to replace with coal tar coke), then
 - 2015 demand: 22.8 million ton/year
 - 2020 projected demand: 27-29 million ton/year
- Current Gross Coal Vol Size - Industrial electrodes presently account for most of the coal-derived synthetic graphite market.
 - At present, needle coke is predominantly produced by the delayed coking of petroleum-derived decant oils (estimated 84% in 2010). The balance is produced from coal tar with 55-85% yield: 120,000 tons of needle coke requiring 0.2 million ton/year of coal tar
 - Aluminum production presently requires 5 million ton/year of coal tar
- Coal tar is a by-product of metallurgical coal coking. Yield of coal tar are roughly 50 lbs per ton of feed coal. Gross coal requirement to satisfy industrial electrode demand is 104 million tons of coal with metallurgical coal tar as the carbonization feedstock. Assuming new emerging on-purpose coal tar technologies of the future could increase coal tar yield by factor of ten, then the gross coal requirement to satisfy industrial electrode demand would be reduced by a factor of ten.
- Future Potential Gross Coal Vol Size – If all industrial electrodes could be entirely from coal-derived, then the
 - Aluminum industry could require 35 million ton/year of carbon anodes, and if an assumption is made that the yield from coking coal to carbon anode is only about 2.7%, then this corresponds to 1300 million tons of coal use (*presuming that new emerging technologies for production of coal liquids can increase yield by a factor of ten, then approximately 130 million tons of coal would be consumed*))
 - Steelmaking requires 750,000 ton/year of graphite corresponding to 27 million tons of coal / year (*2.7 million tons of coal, presuming new emerging technologies for production of coal liquids following similar logic as above*)
- Projected demand for graphite for energy storage may reach 400,000 ton/year by 2020.
 - Satisfied with coal-derived graphite, this demand would correspond to 14.5 million tons of coal / year (*1.45 million tons of coal if emerging technologies are used for production of coal liquids*)
- Required Investment Scale (est.) - For example, deployment of a 60,000 ton/year graphite electrode and cathode plant cost SGL Carbon³⁰ 200 million euro in 2009-2011.

³⁰ <http://www.sglnewsroom.com/pdf/en/reports/report-detail-page.7044.pdf>

- Market Conditions for Profitability - N/A: Carbon material prices are disconnected from oil prices. Price of feedstock (coal tar) may be correlated during times of high oil prices, but for the high-margin carbon products, the feedstock price is negligible.
- Probability of Technology and Market Success - Technologies (industrial electrode and energy storage) and respective markets are well established. Markets for incumbent technology (industrial electrodes) and emerging technology (EV batteries and energy storage) are both growing.
- Cycle Time to Deploy First Commercial Applications - Technologies are available now and are in commercial operation in Asia.
- Regulatory Attributes and Emissions/Water Savings
 - Graphitization is an energy intensive process.
 - SO_x, NO_x and fugitive emissions of VOCs and PAHs need to be addressed in new plant construction.

Coal Use in Metallurgical Applications

Metallurgical processes have used coal for centuries. Coal products are used today in both ferrous- and non-ferrous metals production worldwide, including coal produced in the U.S. The term “metallurgical coal” is commonly applied to coal that is fed to coke ovens. The resultant coke is used primarily in ironmaking blast furnaces, and to a lesser extent for other iron and steel applications and in non-ferrous extractive metallurgy. However, coal products are used in other metallurgical processes without coking. As such, the term “metallurgical coal” herein refers to any coal that finds its way into an extractive metallurgy value chain, and the term “coking coal” is used for coal that is destined for a coking process.

Non-ferrous metal smelting covers three key areas: 1) Aluminum smelting – consumption of pre-baked anode material, 2) EAF Steelmaking – consumption of EAF electrode material (synthetic graphite), 3) EAF Silicon and Ferrosilicon smelting – consumption of EAF electrode material (synthetic graphite). Aluminum smelting and EAF steelmaking have been covered elsewhere in this report. Additional details for silicon and ferrosilicon smelting as additional consumption of both carbon electrode materials and carbon reductant materials are covered in a recent DOE-supported report³¹.

Coal to Carbides

Coal has been part of the global chemical industry since its earliest days. Calcium carbide, for instance, is made by reacting lime with coke – a coal derivative. Acetylene is easily derived from the calcium carbide and yields a range of materials including vinyl chloride for polyvinyl chloride (PVC) plastics and butanediol-based intermediates for spandex polymers. Although the rest of the world has largely switched to petrochemical-based vinyl's, to this day 30 million tonnes of PVC, a major portion of China's PVC, is made from acetylene via this coal-based route.

³¹ Rozelle, P.L., E.W. Leisenring, and M.H. Mosser, 2018, “Coal Upgrading Technologies and the Extraction of Useful Materials from Coal Mine Products: History and Opportunities”, U.S. DOE Office of Fossil Energy, 10.2172/1457712.

Before the petroleum age, acetylene-derived chemicals were the pillar for industrial chemistry. But since the emergence of an alternative feedstock of petroleum-derived ethylene, there's been a progressive reduction in coal-based acetylene production.

Acetylene still holds the promise of serving as a feedstock for aromatics and polyaromatics by new processing routes and new interests in polycyclic aromatics and nanomaterials, such as carbon blacks, which can be derived from acetylene. Other emerging technologies include graphene and carbon nanotubes produced from precursor acetylene. Additionally, new non-calcium lower-temperature routes are being explored as a means increasing the energy efficiency of acetylene production.

Coal to Carbides – Market Attributes

Calcium carbide is mainly produced and consumed in China. The U.S. currently has limited calcium carbide production, with only one large producer³² based in Louisville, KY. The availability of low costs natural gas liquids (ethane) in the US, has created a very competitive ethylene position in the U.S. and favors the petroleum-derived routes currently here in the US. Carbide production cost reductions, by advancing the current state of the technology, could potentially improve competitiveness; e.g. preliminary research has shown that other alkali metals (or possibly catalysts) could be used to lower the processing temperature and improve efficiency by eliminating the requirement for high energy consuming electric arc furnace.

Coal to Graphene

Graphene has been called a “wonder material”, as it offers an unrivalled combination of tensile, electrical, thermal and optical properties. Graphene is flexible and very strong, and in one aspect it is tougher than a diamond and stronger than steel. It is also transparent, impermeable to gases and liquids, and an excellent conductor – even better than gold and copper. These qualities could enable a vast array of breakthrough applications, from ultra-lightweight manufactured products and flexible displays to high-capacity batteries and memory chips to improved water desalinization. Graphene can be made from both anthracite³³ and bituminous coals³⁴.

Graphene could be increasingly incorporated into manufactured products. For example, it could reduce the weight of vehicles, cutting down both fuel consumption and resulting emissions. It is transparent: 97% of light passes through it and it is electrically conductive. This could make it very useful for developing the next generation of electronic devices such as solar panels and batteries. Incorporating graphene into batteries could increase performance via higher energy density, enabling longer cycle times in between recharging.

³² <http://www.carbidellc.com/>

³³ Sasikala, S.P., L. Henry, G.Y. Tonga, K. Huang, R. Das, B. Giroire, S. Marre, V.M. Rotello, A. Penicaud, P. Poulin, and C. Aymonier, 2016, “High Yield Synthesis of Aspect Ratio Controlled Graphenic Materials from Anthracite Coal in Supercritical Fluids”, ACS Nano, Volume 10, 5293-5303.

³⁴ Awasthi, S., K. Awasthi, A.K. Ghosh, S.K. Srivistava, and O.N. Srivistava, 2015, “Formation of Single and Multi-Walled Carbon Nanotubes and Graphene from Indian Bituminous Coal, Fuel, Volume 147, 35-42.

Coal to Graphene – Market Attributes

The global graphene market was estimated at \$25 million in 2015, and is expected to reach \$300 million by 2022, growing at a CAGR of ~44% from 2015 to 2022.

Graphene has gained a foothold in the market in various touchscreen and electronic applications. Additional applications are being developed in the medical technology sector, as further described in the Life Sciences section of this report.

One hurdle for the fledging graphene products is manufacturing of large quantities at scale, in various formats, with high yield and purity and at affordable production costs in order to allow for broader market uptake. This challenge may ultimately be resolved with the use coal as feedstock. Coal is potentially a more economic feedstock than its leading competitor, natural occurring graphite.

In China, a noticeably large effort has been afforded to research and development of this potentially disruptive material. More than 50% of all global graphene related patents currently go to China.

Coal to Building Products (coal fly ash, coal combustion residuals, coal plastic composites).

Coal combustion residuals (CCR) is the latest term of art for the mineral component found in coal or the flue gas desulfurization byproducts resulting from coal combustion for electricity generation. Whether coal is combusted, gasified or treated chemically, the resulting mineral component has value in the construction products industry. Common uses for CCRs include additives to concrete, cement manufacturing, highway construction, wallboard manufacturing, roofing, abrasives, agriculture and various environmental treatment applications.

Historically most coal has been combusted for electricity generation. Extensive regulatory programs and utilization markets have developed around the CCRs produced by the combustion process. CCRs used in a beneficial applications also referred to as CCPs.

Coal plastic composites is an emerging area of potential coal use. In this developing application coal is contemplated as a replacement for wood filler in wood-plastic composites such as in outdoor decking and other uses. Given the early stage of these technologies the reader is referred to the compendium where additional details may be provided by individual technology providers/developers.

Coal to Building Products (coal fly ash, coal combustion residuals, coal plastic composites) – Market Attributes

The American Coal Ash Association (ACAA) performs an annual survey on CCR production and utilization. Based on the latest annual survey³⁵ (2017 data), a total of 111 million tons of CCRs were produced within the electric generation industry. Of that total production, 71.8 million tons or 64.4 %, were utilized in various beneficial uses.

³⁵ Coal Ash Recycling Reaches Record 64 Percent Amid Shifting Production and Use Patterns, Nov 2018, press release, American Coal Ash Association <https://www.acaa-usa.org/Portals/9/Files/PDFs/Coal-Ash-Production-and-Use-2017.pdf>

- **Market** - The U.S. market for CCPs is currently about 70-75 million tons, with the opportunity to grow to a 100 million tons per year. Within each of the major usage categories, the penetration level for the market is low. As an example, the use of CCPs in concrete could be doubled by improvements to consistency of quality and expansion of the available sources with beneficiation technologies. Use of power plant gypsum in wallboard plants only has approximately 50% penetration of U.S. wallboard manufacturing.
- **Gross Market Value** - The market size for the combined uses is estimated to be greater than the total CCRs produced in the U.S. or greater than 150 million ton per year. It is estimated that the current market value is between \$3 and \$5 billion per year. Ironically, the value of CCPs to the U.S. market may have more indirect value than the purchase price of the CCPs. For the current CCPs utilization rate, the avoided costs for disposal are also in the range of \$3 - \$5 billion dollars per year. The intrinsic value of CCPs used in concrete products has the added bonus of reducing about 1 ton of CO₂ emissions per ton CCP utilization as a cement substitute. The CO₂ savings which could be valued at \$20-\$50 per ton or up to \$1.5 billion in total.
- Within the agriculture industry, gypsum is used for its' sulfur nutrient value. Behind nitrogen, phosphorous and potassium (NPK), sulfur is the fourth most necessary nutrient for higher crop yields. Power plant gypsum has a very high purity of calcium sulfate compared to most natural gypsum mined products therefore brings superior value to the agriculture applications as well as to the wallboard manufacturing industry. The value of this market is included in the \$3-\$5 billion products value listed above.
- **Investment Scale** - The markets discussed above are currently achievable market potentials at today's prices. Investments in beneficiation equipment at some sites will be required to grow the market penetration to higher ratios. These investments can be \$25M-\$100M per site, and as many as 20 facilities will need beneficiation installed, for a total of up to \$2.5 billion.
- **Deployment Cycle** - The deployment of beneficiation investments for CCP product expansions can occur very quickly. To develop and install a new project requires approximately 24 months to design, permit and construct the required facilities. Introduction of the new products can take an additional 12-24 months after startup.
- **Regulatory Attributes** - Each beneficiation facility requires permits to construct and operate including air permits, water use and discharge permits and building/construction permits. In many cases the beneficiation equipment will be installed at CCR disposal units which are being reclaimed for the mineral CCPs. This activity is usually permitted by the solid waste permit related to the existing CCR disposal activity or a new reclamation permit.

Coal to Building Products – Emerging Coal Composite Technologies

In addition to the more established uses of coal combustion residuals in building products, several emerging technologies are seeking to use the coal itself as a feedstock for building applications. For example, coal core composites are being developed for use in roofing tiles and fire-resistant panels, and coal plastic composites are being developed as an alternative to the wood plastic composites commonly used in decking applications. These products show potential for being disruptive by offering certain cost and performance advantages (e.g., flexure strength, moisture resistance, and fire resistance) relative to currently-used materials, and do not require combustion or conversion of the coal, resulting in very low emissions.

Coal to Carbon Foam

Carbon foams made from coal also show potential for use in building material and structural applications, such as aggregate for lightweight concrete, proppants, non-combustible building materials, and components used in transportation and military defense items, which have the potential to grow to meaningful volumes. Currently, coal-derived carbon foam is being used commercially in small-volume, high-value applications with stringent performance requirements, including as a tooling material in the production of carbon-fiber composites for aerospace, military, and commercial goods

Graphitic carbon foam has a highly-oriented, low density graphite foam structure. Its main benefits include high performance attributes such as extremely high thermal conductivity, high compressive strength, high electrical conductivity, near-zero coefficient of thermal expansion and extreme lightweight properties.

The U.S. is the main consumption region (>90% of global consumption), dominated by demand from aviation, automotive and electronics sectors in which an increasing number of applications are requiring more efficient lightweight thermal management such as in high-density electronics, hybrid diesel-electric vehicles, communication satellites and advanced aircraft.

The market for carbon foam is estimated at \$23M in 2017 and growing at CAGR rate of 6%, expected to reach \$37M by 2025. Price of current carbon foams are relatively high, up to 500 \$/kg. At the time of this writing, annual consumption volumes were not known; a simple estimation based on market and price per kg would indicate a relatively small volume of about 151 tons, likely used in specialty aerospace and defense applications.

Coal to Carbon Black

Carbon black is used to improve certain properties of the materials to which it is added, primarily for abrasion resistance in rubber tires and other rubber products; as a black pigment in coatings, printing inks, and plastics; and for conductive properties in some polymers and resins.

Production economics are very dependent on the specific feedstock for carbon black manufacturing. Coal-based feedstocks in China are supplied from massive metallurgical coking operations, typically enjoying a lower cost position than petroleum-derived carbon black feedstocks. The growth of carbon black is closely tied to the automotive industry and the production of tires. With the global automobile industry moving east to China, India, and Central and Eastern Europe, the tire industry has followed, and with it the carbon black producers.

Coal to Carbon Black – Market Attributes

- **Market** - The global carbon black market is expected to surpass \$25 billion by 2020, growing at a CAGR of over 4%.
- **Industry Supply** - The total global capacity of carbon black stood at ~16 million tonnes in 2017, with China as the largest producer accounting for ~43% of the global capacity with more than 100 plants running. China is also the largest global consumer at 35%. China has experienced strong growth in the export volumes of carbon black, ~52% CAGR, during the period of 2010-14. China produces nearly 7 million tonnes per year of carbon black from wholly coal-derived feedstock.

The global carbon black industry is concentrated in nature, with the top 10 players controlling ~ $\frac{2}{3}$ of global capacity. The industry as a whole, exhibits relatively

1. High capital intensity
 2. Project deployment cycle time (~2 years)
 3. Customer qualification timelines, due to stringent quality requirements (18-24 months)
- **U.S. Competitiveness** - The major proponent of growth for Chinese exports of carbon black has been the distinct cost advantage over global peers, which emerged as a result of the use of coal tar oil as the raw material feed. Coal tar is available in large quantities in China because it is a by-product of coking processes. China's carbon black exports grew rapidly starting in 2011 and then stabilized to around 640 thousand tonnes per year after 2014. This led to the capture of significant volume share by Chinese manufacturers. This phenomenal rise in the Chinese exports for carbon black also resulted in a situation of excess supply in the global industry.

In theory, the opportunity exists for U.S. coal to play a similar role in the carbon black market. In practice however, the U.S. metallurgical coal coking industry is relatively small in comparison to China's; and much of today's coking capacity in the U.S. does not recover the coal tars, instead consuming these directly for integrated on-site heating purposes. New specialized on-purpose coal to coal tar technologies would need to be developed and commercialized.

- **China Coal Tar Industry and Implications** - As it relates to carbon black, a closer look at China's coal tar sector is illustrative, especially considering the upward of 20 million tons of coal-derived products that result from the coal tar industrial sector. High-temperature coal tar from the metallurgical coking industry, holds a dominant position in the Chinese market. In 2016, 16 million tons of high-temperature coal tar (from coking operations) and 4 million tons of medium-temperature coal tar (from pyrolysis processes) were produced. High-temperature coal tar from metallurgical coal coking operations were primarily used in high-value-added chemicals while medium-temperature coal tar was used in the fuel oil field, it is expected the former will grow faster than the latter.

China currently holds a position as the world's leader in metallurgical coke production. China's coke output has remained fairly stable over the past few years at ~420 million tons a year, accounting for 69% of the total global volume. Similarly, China's coal tar output, a byproduct of coking operations, kept pace at around 16 million tonnes per year (~4% of coke output). In 2017, the majority of this output was consumed by two large sectors, also shown below in Figure Appendix A-7:

1. Coal tar distillate products (pitch, anthracene, naphthalene), comprising about 12 million tonnes (74%)
2. Direct feedstock to carbon black at 3.5 million tonnes (21%) direct consumption, noting that carbon black processes can also consumes other coal tar distillate derivatives

Key Highlights

- China retains a very large scale and robust coal tar industrial segment.
- The supply chains have evolved along the lines of both specialty and commodity product lines, which compete directly with petroleum derived products.
- Market sectors which are growing include graphite materials for electrodes and anodes, carbon black and phthalic anhydride. All enjoy relatively high margins in large part due to the low price of coal, buoyed by the relatively high price of crude oil, which is customarily used as the key feedstock for competing products on the market.
- In China, it is also reported that coal tar serves as raw material for pharmaceuticals, agricultural chemicals, dyes, and synthetic fibers. At the time of this writing it was not known to what extent China is producing these specific specialty products from coal tar.
- These and other questions about China's coal-to-products industry are relevant to U.S. strategic interests and would be worthy of further analysis.

Matallurgical Coke Output 415 Mio tonnes	Coal Tar Liquid Output 16.45 Mio tonnes (4% of coke)	Coal Tar Distillation 12.21 Mio tonnes (74% of CTL)	Coal Tar Pitch 5.5Mio tonnes	Prebaked Al Anodes EAF Steel Electrodes Needle Coke	3.26
				Export	0.62
				Fuel oil	0.1
				Other	0.35
				Carbon Black	1.20
			Anthracene Oil 2.54 Mio tonnes	Carbon Black	2.21
				Hydrogenation	0.14
				other derivatives	0.075
				Export	0.028
			Naphthalene Oil 1.26 Mio tonnes	Phthalic anhydride	0.84
				Water reducer (FDN)	0.24
				Dyestuff intermediate	0.20
				Export	0.00
			Carbon Black 3.45 Mio tonnes (21% CTL)		3.45
			Fuel oil, hydrogenation, other		

Figure Appendix A-7. China Coal Tar Industry Structure – 2017 Estimations ^{36, 37}

Coal Derived Rare Earth Elements and other Critical Minerals

REEs and other critical minerals (CMs) are used in end products in critical sectors of the U.S. economy that include health care, military, transportation, power generation, petroleum refining, and electronics. Specific REE applications include magnets for wind turbines, batteries and magnets for vehicles, and phosphors for lighting products. As of 2014, the use of these elements, as reported by the American Chemistry Council, was supportive in North America of over \$329 billion of economic output, with an associated employment figure of over 618,000 people.³⁸ The most valuable of these are the heavy REEs.

REEs that are commercially produced include 14 different elements that occur in nature and are produced together. Various elements find uses in different applications and the markets for individual elements are complex.

³⁶ BAI INFO Report entitled “China Coking Industry Overview - China Coal Tar Demand & Supply Analysis” by ZHANG Mi, from July 2018 <https://www.itaorg.com/conference-pdfs/presentation08-day1-Zhang.pdf>

³⁷ The accuracy of the BAI INFO report has not been further tested or validated. Some of the numbers may not be consistent with other sources, for example, this report does not appear to take into account the low temperature coal pyrolysis market in China is estimated to be about 4 million tonnes/year

³⁸ American Chemical Council, The Economic Benefit of the North American Rare Earths Industry, Economics & Statistics Department, American Chemistry Council, April 2014.

In May 2018, the Department of the Interior (DOI) published its “Final List of 35 Minerals Deemed Critical to U.S. National Security and the Economy”³⁹ which was compiled in response to White House Executive Order 13817, “A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals.” Some items on the Critical Minerals list, such as vanadium and germanium and other REEs, have been commercially extracted directly from coal products. In other cases, coal is used as a reagent in the extractive metallurgy processes used to produce these commodities.

However, the U.S. is virtually 100% import-dependent for the raw materials for its REE-based manufacturing sector. Restarting production of rare earth commodities from U.S. mineral deposits can improve national security and help assure that the related manufacturing base and supply remains secure within the U.S. and grows.

REE extraction from U.S. coal and coal byproducts can have numerous advantages, including the development of domestic REE sources, use of the existing supply chains and labor force in U.S. coal-producing regions, and providing for economic improvements in those regions.

A proportion of coal deposits are naturally rich in rare earth elements (REE). The extraction of REE from raw coal or coal by-products (tailings, ash and aqueous effluent) holds real promise as an important method to secure the industrial supply of critical elements. A number of different groups are pursuing various technical paths that will result in viable options for commercial domestic production of REE oxides. Coal as a source of minerals has a history dating back to the 1940s when uranium was first extracted from coal seams. For this new REE-coal initiative the presence of a pre-existing mine operation and material handling systems may make the industry more competitive. Continued support at the federal level will be critical as these options move from bench to pilot-scale and finally commercial demonstration.

Coal Derived Rare Earth Elements and other Critical Minerals – Market Attributes

- U.S. Competitiveness – Currently the U.S. imports 100% of the REE from China. Due to the strategic importance of these materials, the U.S. needs to identify domestic sources for REE. In addition to the economic benefit to the U.S. provided in the overview above, a significant amount of the total U.S. consumption supports the U.S. military. For example, the U.S. Airforce and U.S. Navy both use sizeable amounts of RREs to produce advanced aircraft and naval vessels.
- Current Gross Market Rev Size - The global Rare Earth Elements market in 2015 was estimated to ~\$5B (130,000 metric tonnes/yr)⁴⁰. The major producers include China – 105,000 tonnes per year, Australia – 20,000 tonnes per year, Russia – 3,000 tonnes per year. Only minor amounts were mined in Brazil, India, Malaysia, Thailand, and Vietnam. Mine production from RRE ore was zero in US. Neither have REE’s been commercially derived from coal or coal byproducts at the time of this writing.

³⁹ Final List of 35 Minerals Deemed Critical to U.S. National Security and the Economy
<https://www.federalregister.gov/documents/2018/05/18/2018-10667/final-list-of-critical-minerals-2018>

⁴⁰ https://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/myb1-2015-raree.pdf

- Required Investment Scale - REE could be recovered either from coal or from coal by-products. For REE recovered from lignite coal, it is estimated that the minimum size for a commercial facility would be 50 ton/hour and would result in salable product of either upgraded coal or activated carbon. For either tailing from a bituminous coal cleaning facility or acid mine drainage, the expected size for a commercial operation is not known at present.
- Value Chain opportunities that could be realized using REE domestically produced from coal or coal by-products shown below in Figure Appendix A-8.

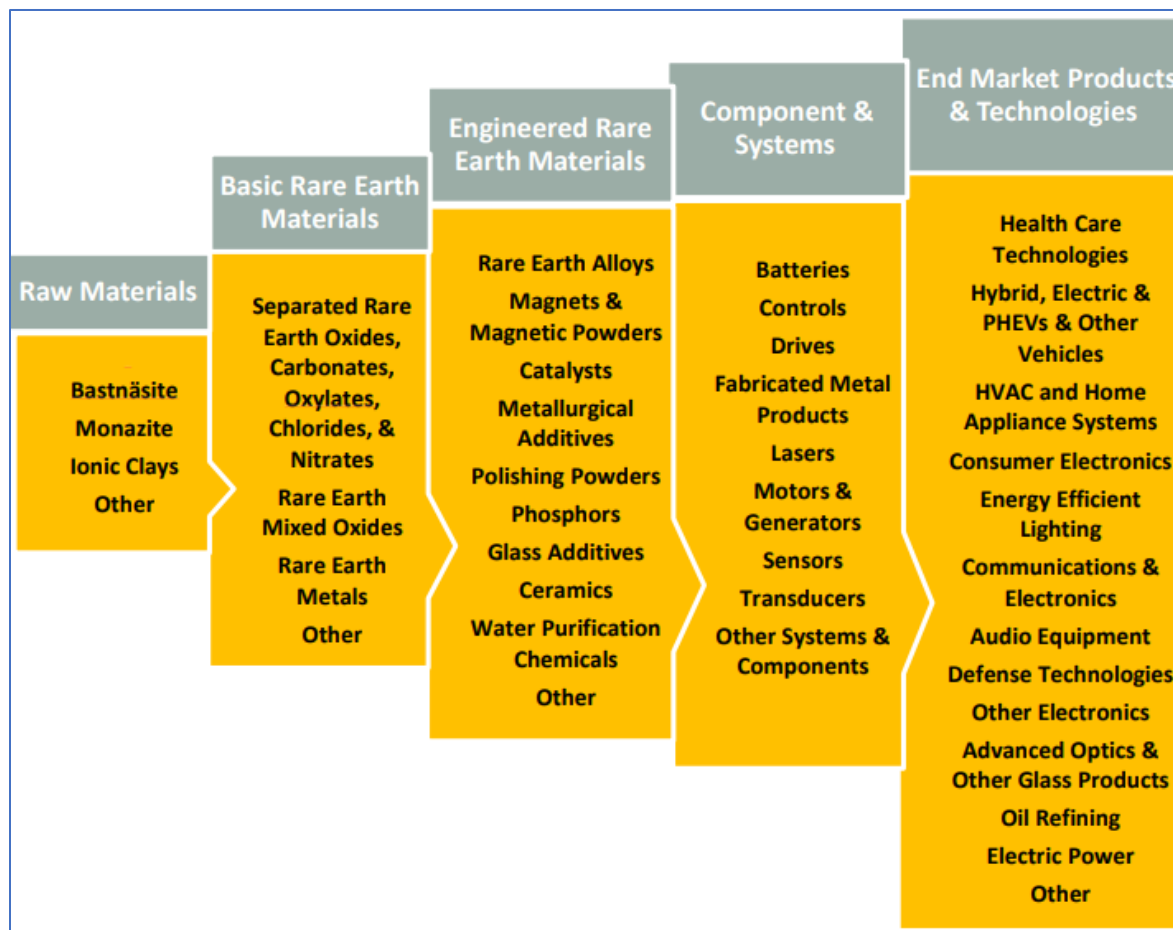


Figure Appendix A-8. The Rare Earth Value Chain ⁴¹

⁴¹ <http://www.rareearthtechalliance.com/Resources/The-Economic-Benefits-of-the-North-American-Rare-Earths-Industry.pdf>

Life Sciences and Medical

The history of coal in the chemical and pharmaceutical industry can be traced to the discovery and development of synthetic dyes from coal tar – a byproduct of town gas and the steel industry. In 1856, the first synthetic aniline purple dye was extracted from coal tar. During this period of history, the synthetic dye industry was the “high-tech” industry.

Modern pharmaceuticals have their origins in apothecaries (e.g. Merck, Schering, Hoffman-La Roche, Abbott, Eli Lilly, and Burroughs-Wellcome) that commenced to produce and sell drugs extracted from flora and fauna as well as in the organic chemical companies – especially dyestuffs⁴² – (e.g. Bayer, Sandoz, Pfizer, and Hoechst) that moved from manufacturing dyes through extraction from coal tar to other organic chemicals, using the organic building blocks extracted from coal and coal byproducts. The development of pharmaceutical and medicinal chemistry, as well as pharmacology, as areas of rigorous research was the inflection point of apothecaries and the organic chemistry companies becoming blended into a recognizable pharmaceutical industry.^{43, 44, 45}

- Graphene Medical Potential - Graphene’s unique physical structure, as well as its chemical and electrical properties, make it ideal for use in sensor technologies. In the past years, novel sensing platforms⁴⁶ have been proposed around graphene. Several of these platforms were used to immobilize biomolecules, such as antibodies, Deoxyribonucleic acid (DNA), and enzymes to create highly sensitive and selective biosensors. The main reason for researchers to use this detection approach is that it is simple, rapid and presents good sensitivity. These coal-based biosensors can be particularly useful in life sciences and medicine, since biosensors with high sensitivity and specificity can significantly enhance patient care, accurate early diagnosis of diseases and pathogen detection in clinical practice.
- The markets for bio-sensors are both large in terms of near term revenues and at growth rates well above global GDP. Some examples of near term project revenues and growth: Rapid diagnostics (\$38B, 7.6% CAGR), Cancer detection (\$232B, 19.6% CAGR), Sequencing (\$18B, 8.0% CAGR), Environmental and lab sensor (\$20B, 7.7% CAGR).

BioTech and Agricultural Uses

Lignite coal has a history of use as a fertilizer; it is currently being assessed as a large-scale solution to help counter the problem of desertification with remediation. If upgraded lignite coal performs as an effective agricultural additive, then this could be a significant alternate high-volume use of a valuable resource.

⁴² Chemical and Engineering News, Emergence of pharmaceutical science and industry: 1870 – 1930.

⁴³ *Understanding technology adoption in the German pharmaceutical industry*. Lacasa, Iciar Dominguez. January 16-18, Karlsruhe, Germany : DRUID Academy Winter 2003 Ph.D. Conference, 2003.

⁴⁴ CEN. Emergence of pharmaceutical science and industry: 1870 - 1930. *Chemical & Engineering News*

⁴⁵ *Early drug discovery and the rise of pharmaceutical chemistry*. Jones, Alan Wayne. Historical, s.l. : Wiley Online Library, 2011, Vol. Drug Testing and Analysis.

⁴⁶ *Creating a Standardized Approach for Developing Medical Grade 2D Materials*. Nichols, GP. 1, Oak Ridge, TN : Trends in Nanotechnology & Material Science (Exceyitics Publishers), April 4, 2016, Vol. 1.

Lignite contains natural organic compounds known as humate, which are from the decomposition of plants and are found in soil, peat, as well as lignite⁴⁷. Application of humates to soils is beneficial, promoting increased water retention, growth of beneficial micro-organisms, root growth, and plant yield serving as a source of natural nutrients and replacement of lost top soil. The environmental applications include removal of toxic metals, organics and radionuclides by adsorption of acidic water streams and reduction of harmful metal species. Organic fertilizer made from lignite coal is increasingly in use to improve soil fertility, improve efficiency of mineral fertilizers and overcome drought and salinity impacts.

Humate and humic acid products could play an important role in counteracting the deterioration of fertile land, a challenge caused by intensive farming, erosion and drought.

By one estimate, up to 50 million acres of agricultural land in North America would benefit from the application of humic acid products. As an illustration of the future potential, if 10 ton/acre were applied to 1 million acres annually, this would equate to 10 million ton per year of humate product usage.

The economic value of the industry depends on the adoption of humate technology to replace and, to a certain extent, supplement chemical fertilizers. The value of the humates industry will depend on demonstration of proven long-term fertility benefits, water retention and NPK fertilizer retention benefits.

⁴⁷ *Review: Commercial Humates in Agriculture: Real Substances or Smoke, and Mirrors?* Grapham Lyons, and Yusuf Genc. s.l.: Agronomy, 2016, Vol. October 2016

APPENDIX B

TECHNOLOGY COMPENDIUM

A stakeholder survey was conducted to gather information on activities to develop technologies for producing fuels, chemicals, rare earth elements, and carbon-products from coal. Stakeholders provide their own assessment of technology maturity and market potential against 13 metrics shown in the following three tables. Stakeholders self-ranked the maturity and market potential using a scale from 1 to 9 with 9 being the highest rating.

PLEASE NOTE: NCC has included information in this appendix on an “as submitted” basis based on submissions by survey respondents; NCC has not verified any of the information submitted and is not responsible for the accuracy of the information submitted.

Table Append B-1. Technology Maturity and Market Opportunity Matrix

Technology	Technology Stage	Scale Demonstrated	Timing of Prototype	Timing of Pilot	Timing of Full-scale	Timing of commercial deployment	Economics Stage	Investment Stage	Potential U.S. coal utilization	Price comparison	Competitiveness	Environmental Impacts	National Security
Carbon Fibers													
Green Coal Solutions	9	9	9	9	9	9	9	9	4	9	9	9	9
Penncara Synpitch	5	4	4	N/A	5	5	6	N/A	3	6	9	9	9
Wave Liquefaction Carbon Fiber - H-Quest	1	1	5	5	5	6	4	3	6	9	9	9	9
Rare Earth Elements													
CCR-to-CCP Rare Earth Elements - RamRock	1	1	1	1	2	2	7	3	2	9	9	9	9
CTC Foundation Coal derived REE	6	3	6	7	7	7	5	4	6	8	9	9	9
Microbeam Technologies Recovery of REE	3	3	1	2	5	5	2	3	3	5	5	9	9
Remedial Coal Solutions - CBA Environmental	7	5	9	9	7	7	9	9	9	9	9	9	9
Southern Illinois University - Hybrid Nanofibers	x	x	x	x	x	x	x	x	x	x	x	x	x
Southern Illinois University - REE & Transition Metals	x	x	x	x	x	x	x	x	x	x	x	x	x
Building Materials													
CCR-to-CCP Flowable Fill - RamRock	9	5	9	9	9	7	9	9	4	9	9	9	1
CCR-to-CCP Concrete - RamRock	9	9	9	9	9	7	9	3	9	9	9	9	1
CFOAM Carbon Foam Products	4	4	5	5	5	5	5	5	8	5	9	9	9
CO2 Concrete, LLC	4	4	9	7	5	5	5	3	9	5	9	9	5
CTC Foundation Fly Ash & CCR to Building Products	6	4	6	6	5	5	7	5	6	6	8	9	4
Green Coal Solutions	9	9	9	9	9	9	9	9	4	9	9	9	9
Ohio University Coal Plastics Composites	4	4	9	7	5	5	7	5	2	9	9	9	1

Table Append B-1. Technology Maturity and Market Opportunity Matrix (continued)

Technology	Technology Stage	Scale Demonstrated	Timing of Prototype	Timing of Pilot	Timing of Full-scale	Timing of commercial deployment	Economics Stage	Investment Stage	Potential U.S. coal utilization	Price comparison	Competitiveness	Environmental Impacts	National Security
Life Science Applications													
NOVIHUM - Novihum Technologies	8	7	9	9	9	5	6	9	4	5	9	9	5
Transportation Fuels													
Benepius - LP Amina	6	5	9	9	7	7	5	5	8	8	8	8	8
Carbide - LP Amina	3	3	7	5	3	2	5	1	8	8	8	7	7
CTC Foundation Coal to Syngas	8	4	6	7	6	6	6	4	7	7	8	9	8
DryFining - Great River Energy	x	x	x	x	x	x	x	x	x	x	x	x	x
Gen2, LLC - Gen Tech PTD, LLD	4	4	9	5	5	5	7	5	6	7	9	9	9
H-Coal - Axens North America	7	7	9	9	9	7	9	7	8	7	9	9	9
Riverview Energy	x	x	x	x	x	x	x	x	x	x	x	x	x
Southern Illinois University - Coal to Liquid Fuels	x	x	x	x	x	x	x	x	x	x	x	x	x
Synfuels Americas Fischer-Tropsch Synthesis	9	9	9	9	9	9	7	4	9	4	9	5	9
Synfuels Americas Stepwise Liquefaction	5	4	1	5	2	4	5	5	9	5	9	5	9
Wave Liquefaction Transportation Fuels - H-Quest	6	4	9	6	4	4	5	3	9	9	9	9	9
Other - Activated Carbon													
CCR-to-CCP Activated Carbon- [RamRock	1	2	5	5	5	7	7	3	4	9	9	9	1
Other - Coal Beneficiation													
DryFining - Great River Energy	x	x	x	x	x	x	x	x	x	x	x	x	x
Wave Liquefaction Coal Beneficiation - H-Quest	6	4	9	6	4	4	5	3	9	9	9	9	1

Table Append B-1. Technology Maturity and Market Opportunity Matrix (continued)

Technology	Technology Stage	Scale Demonstrated	Timing of Prototype	Timing of Pilot	Timing of Full-scale	Timing of commercial deployment	Economics Stage	Investment Stage	Potential U.S. coal utilization	Price comparison	Competitiveness	Environmental Impacts	National Security
Other - Chemicals & Petrochemicals													
H-Coal - Axens North America	7	7	9	9	9	7	9	7	8	7	9	9	9
Synfuels Americas Stepwise Liquefaction	5	4	1	5	2	4	5	5	9	5	9	5	9
Wave Liquefaction Chemicals - H-Quest	6	4	9	5	5	4	5	3	6	7	9	9	9
Other - Graphite													
Penncara Synpitch	5	4	4	N/A	5	5	6	N/A	3	6	9	9	9
Wave Liquefaction Graphite - H-Quest	1	1	5	5	5	6	4	3	6	9	9	9	9
Other - Nanoparticles & Nanotubes													
CTC Foundation Nanoparticles	4	3	5	7	5	5	7	5	4	8	8	9	8
Southern Illinois University - Carbon Nanotubes	x	x	x	x	x	x	x	x	x	x	x	x	x
Other - Hydrocarbons													
Benepius - LP Amina	6	5	9	9	7	7	5	5	8	8	8	8	8
Other - Soil Amendments													
CCR-to-CCP Soil Amendment - RamRock	4	5	9	9	9	7	9	3	4	9	9	9	1
Other - Compounds													
CCR-to-CCP Magnesia - RamRock	1	2	1	3	2	5	7	3	4	9	9	9	1
Southern Illinois University - Silicon Carbide-Alumina	x	x	x	x	x	x	x	x	x	x	x	x	x
Other - Mineral Fiber-Paper Pulp													
Green Coal Solutions	9	9	9	9	9	9	9	9	4	9	9	9	9

The stakeholder survey criteria are shown in Table Appendix B-2. Each stakeholder survey response is provided after this table.

Table Appendix B-2. Technology Maturity and Market Opportunity Survey Criteria

		Matrix Entry								
Topic		1	2	3	4	5	6	7	8	9
Development phase	Technology Stage	Concept / White paper			Feasibility confirmed; commercial case promising			Investment ready		Commercial
	Scale Demonstrated	None	Lab	Bench	Small Pilot (<10% of full scale)	Large Pilot (>10% of full-scale)		Demo/FOAK		Commercial
	Timing of Prototype	> 1 year				<6 mo				Complete
	Timing of Pilot	unknown	>3 year	2-3 year		1-2 year		<1 year		Complete
	Timing of Full-scale demonstration (FOAK)	unknown	>5 year			1-2 year		<1 year		Complete
	Timing of commercial deployment	unknown	>10 year			3-5 year		1 year		Complete
	Economics Stage (Cost accuracy range, e.g. +/- 30%)	unknown	unknown			+/-50%		+/-30%		+/-10%
	Investment Stage	unknown		Govt Grant		Other Gov't support needed (describe in survey)				Investment Grade Financeable
Business Case	Potential U.S. coal utilization, magnitude (MMton/yr)	<1	>1	>5 MM	>10		25-50		50-100	>100 MM
	Price comparison - cost-competitive advantage over alternative	More expensive				Neutral		10% less		>20% less
	Competitiveness (benefits other than price)	None				1 key benefit				2+ key benefits
	Environmental Impacts	net increase				Neutral				net benefit
	National Security	Neutral				1 benefit				2+ benefits
<p>"Investment Stage": refers to ability to access investment financing to deploy the technology</p> <p>"Competitiveness" key benefits include: jobs, better utilization of resources, environmental, national security</p> <p>"National Security" benefits include: reducing import dependency, providing redundancy of sourcing, improving trade</p> <p>"FOAK": First of a kind</p>										

Technology Overview

H-Coal®

Axens North America | John Duddy

650 College Road East, Princeton NJ 08540 | 609-987-3027 | john.duddy@axens.net

MARKET SECTOR AND SIZE

-
- | | | |
|---|---|--|
| <input type="checkbox"/> Carbon fibers | <input type="checkbox"/> Carbon resins | <input type="checkbox"/> Rare earth elements |
| <input type="checkbox"/> Sorbents | <input type="checkbox"/> Building materials | <input type="checkbox"/> Life science applications |
| <input checked="" type="checkbox"/> Other: Petrochemicals (BTX) | | <input checked="" type="checkbox"/> Transportation fuels |
-

The H-Coal Process licensed by Axens is an advanced direct coal liquefaction technology that is fully developed and is ready for commercial application. The coal liquefaction technology, uses the same technology as the commercial H-Oil® Process for heavy oil upgrading, has been tested at the bench unit scale (50 lb coal /day), Process Development Unit scale (3 Ton coal /day), and the Demonstration Plant scale (200 Ton coal/day). Axens prepared the design and startup of the first commercial scale direct coal liquefaction plant (6,000 Metric T coal/day producing 20,000 BPSD of liquid fuels) for Shenhua in Inner Mongolia, China which started operations in 2008. The H-Coal Process has been successfully applied to a wide range of coals including bituminous, sub-bituminous, and lignite. The H- Coal Process produces high yields of distillate liquid products from coal. These coal liquids are upgraded using Axens' commercial refining technologies to make on-specification transportation fuels. A large size single train H-Coal Plant process about 2.5 MMTPA of coal and produces 10-Million barrels per year of transportation fuels and LPG. Alternatively, the product upgrading can produce petrochemicals production with high selectivity to paraxylene.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☐ 1 to 10 ☐ 10 to 25 ☒ 25 to 50 ☐ 50 to 100 ☐ >100

LARGEST SCALE DEMONSTRATED

-
- | | | |
|--------------------------------------|--|--------------------------------------|
| <input type="checkbox"/> None | <input type="checkbox"/> Laboratory or bench formulation | <input type="checkbox"/> Small pilot |
| <input type="checkbox"/> Large pilot | <input type="checkbox"/> First-of-a-kind demonstration at full scale | <input type="checkbox"/> Commercial |

The basic process flow scheme, ebullated-bed reactor, pilot units and development path is the same as that used in the commercial H-Oil Process. Axens was selected by Shenhua to provide Basic Engineering Design and technical support services for DCL plant based on the extensive experience with heavv oil conversion and coal liquefaction.

TIMING

Full commercial availability is feasible within:

- ☒ 1 year ☐ 3 years ☐ 5 years ☐ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒Reduction of import dependence ☐Enhancement to international trade

☒Provides redundancy of sourcing ☐ Other: _____

ECONOMIC ☒Job creation ☒Economic support to region in downturn

☐Price advantage over alternative ☐ Other: _____

OTHER ☒Environmental improvement ☒Improved resource utilization

☐ Other: _____

- Reduction of net imports of crude oil and petroleum products.
- Utilize existing/idle coal production capacity.
- Revitalize economy in coal producing regions impacted by mine closings.
- Opportunity to utilize existing and idle coal processing facilities.
- Jobs creation for operation, maintenance and management of coal liquefaction facilities (approximately 500 per facility) plus associated indirect jobs creation.
- Jobs creation for facility construction. Peak construction jobs creation is typically more than 1000 skilled laborers.
- Clean coal technology. Produces completely fungible liquid transportation fuels with low emissions compared to coal combustion.
- Opportunity to synergistically utilize abundant and low cost coal and natural gas resources. Natural gas can be efficiently utilized to provide a low-cost source of hydrogen for direct coal liquefaction. Synergy readily exploitable in hard-hit Appalachian coal production which growing shale gas production.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

Capital investment requirement is approximately \$100,000/BPD of capacity. Consider a minimum economically viable production capacity to be 10,000 BPB, with capital investment of \$1-Billion.

What is the magnitude and type of investment needed to take this technology commercial?

Technology is fully developed and commercially available.

What major hurdles or barriers to next steps of development need to be addressed?

Full-scale commercial development efforts in the U.S. have historically been hampered by oil price volatility. This has made project financing difficult.

Technology Overview

Remedial Coal Solutions (RCS)

CBA Environmental Services, Inc. | Bruce L. Bruso

57 Park Lane, Hegins, PA 17938 USA | 570-682-8742 | bbruso@cbaenvironmental.com

MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☒ Rare earth elements
☐ Sorbents ☐ Building materials ☐ Life science applications ☐ Transportation fuels
☒ Other: Improving the Competitiveness of U.S. Coal, reduction of CO₂ & all GHG's, and increased reliability of base-load power plants through gains in efficiency & reduced cost of generation while recovering REE's

The RCS process is a modular and scalable pre-combustion coal enhancement process utilizing proprietary chemistry and standard mineral & aggregate processing equipment to improve ROM thermal coal resulting in better power plant heat rates and efficiencies while significantly reducing CO₂ and other GHG's. The process reduces costs of generation and O&M of emission controls.

The RCS process while improving moisture and calorific value, can reduce other pollutants without having to pulverize or briquette the coal. RCS coal will not spontaneously combust, reabsorb moisture or increase friability during transportation, handling or storage.

RCS refined coal creates a dual benefit in that RCS treated coal provides multiple benefits to the US-base load coal-fired generation fleet, while also increasing the export market value of U.S. coal, while providing a major contribution to U.S. Energy Dominance.

The RCS process also can improve the quality of off-spec and waste metallurgic coking coals by removing oxidation, increased transmittance, fluidity & reactivity promoting the reuse of millions of tons of thermal and coking coal impoundments by re-entry into applicable markets at current benchmark values.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☐ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☐ 50 to 100 ☒ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☐ Laboratory or bench formulation ☐ Small pilot
☒ Large pilot ☐ First-of-a-kind demonstration at full scale ☐ Commercial

CBA operated a large pilot plant for 4 years at CBA's corporate facility. Today, through an external equipment manufacturer, a 500-lb per hour full flow-through unit is available for client demonstrations and preparation of reasonable volumes of refined coal in order to carry out independent combustion testing and analysis.

TIMING

Full commercial availability is feasible within:

- ☒ 1 year ☐ 3 years ☐ 5 years ☐ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒Reduction of import dependence ☒Enhancement to international trade

☒Provides redundancy of sourcing ☒ Other: Substantial contribution to increasing the competitiveness of U.S. coal and the desire to be energy dominant.

ECONOMIC ☒Job creation ☒Economic support to region in downturn

☒Price advantage over alternative ☒ Other: Reduction of power generation costs across the chain, and increased efficiency and reliability of base-load coal-fired power generation. Economic diversification and creation of commodity arbitrage that can hedge against market swing.

OTHER ☒Environmental improvement ☒Improved resource utilization

☒ Other: Significant reduction of CO₂ and CO₂-e - qualified carbon oxides as well as other GHG's. Increased power plant efficiency, base-load reliability and reduced derates.

Expand on the indicated benefits of this technology in 200 words or less (for example, quantify number of manufacturing jobs created at a specified scale if "job creation" is checked):

Creation and preservation of up to 60-100 jobs per RCS facility deployed including direct and indirect jobs. Increase the competitiveness of U.S. coal. Substantial contribution to U.S. - energy dominance status. Reduced cost of power generation across the entire power generation chain. Reduction of as much as 50% - 60% CO₂ and CO₂-e as well as Greenhouse Gasses (GHG's). The RCS process is a near-Zero-emission process that also produces strategic metals and REE's from the process providing for a positive, dual cost-benefit-analysis that improves the value of the coal while optimizing the fuel for the power plant, and recovers strategic metals and REE's with one single-train processing application and cost. Creation of coal export arbitrage.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

\$20-million. A Government-Industry joint investment should be taken into consideration.

What is the magnitude and type of investment needed to take this technology commercial?

\$20-million.

What major hurdles or barriers to next steps of development need to be addressed?

Investment. The technology owner and industry participants have advanced this technology to commercial-ready status with investment of over \$15-million to date with no investment from the U.S. government.

Technology Overview

CFOAM[®] Carbon Foam Products

CFOAM[®] LLC - Rudolph Olson III, PhD

The Millennium Center - 1142 Middle Creek Rd., Triadelphia, WV 26059

Office: 304-907-2501 - Cell: 828-489-4531 - rolson@cfoam.com

MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☒ Building materials ☐ Life science applications ☐ Transportation fuels
☒ Other: _____

CFOAM[®] Carbon Foam is a strong, machinable, non-combustible, and lightweight material enabling a host of next-generation technologies. The first large-scale CFOAM[®] commercial product is a tooling material used in the production of carbon-fiber composites for aerospace, military, and commercial goods. CFOAM[®] tools have been used to build components for rockets, aircraft, satellite dishes, and naval ships. We expect the carbon-fiber composite market to continue to expand rapidly as their use is further integrated into society. Several other CFOAM[®] products having much larger markets are being considered today, including high-temperature kiln components, aggregates for high-temperature refractories and lightweight concrete, proppants, non-combustible building materials, and components used in large military defense items. We believe these markets could use over 50 million tons of coal. Currently the product line is supported by 27 patents with more in the works generated by an active R&D program. Lastly, CFOAM[®] carbon foam is considered to be a very green material relative to coal, as most of the coal becomes sequestered as an amorphous, inert carbon. In the future, further green refinements are possible through recycling of process scrap back into the product and using volatiles to support thermal processing steps.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☐ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☒ 50 to 100 ☐ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☐ Laboratory or bench formulation ☐ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☒ Commercial

CFOAM[®] LLC supports the aerospace composites market with a capacity of 25,000 ft³. CFOAM is growing rapidly and scalable to capacities which could utilize >50-million tons. CFOAM is used in many DOD platforms and the business focus is on high-value applications, but the technology is scalable to a huge platform.

TIMING

Full commercial availability is feasible within:

- ☐ 1 year ☐ 3 years ☒ 5 years ☐ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒ Reduction of import dependence ☐ Enhancement to international trade

☒ Provides redundancy of sourcing

☒ Other: New technologies that enhance the ability of the U.S. to protect itself.

ECONOMIC ☒ Job creation ☒ Economic support to region in downturn

☐ Price advantage over alternative ☒ Other: Added value over existing products.

CFOAM® carbon foam has grown 300% in 24 months making a coal-based product used by virtually all U.S. aerospace companies and we have already created about 50 jobs. It has been deployed in Iraq to absorb radar, built parts which have flown on aircraft in Afghanistan, and has built rocket nozzles for U.S. rockets. CFOAM, Ltd has been focused on high value, small market CFOAM® carbon foam applications. This technology is a great, high value job creator – adding an order of magnitude of labor per ton of coal; the coal grows in value as it becomes an advanced material.

By adding an additional business strategy – focusing on very large applications – such as aggregate for lightweight concrete or proppants (>50 million tons in North America in 2017), we could also maximize the use of coal. The base CFOAM® technology that was originally funded through SBIR programs from the Navy, Air Force, and Department of Energy is solid and proven at scale. The ultra large volume applications will need some research funding to make them a reality quickly. CFOAM® carbon foam holds the promise of a large-scale, environmentally friendly industry that sequesters carbon and could produce energy as a by-product.

OTHER ☒ Environmental improvement ☒ Improved resource utilization

☐ Other: _____

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

Tripling capacity will cost about \$23 million and this can be done at our current location along I-70 just outside Wheeling, WV. Expanding this plant will add about 185 new jobs with both this plant and its largest customer located in the same industrial park.

What is the magnitude and type of investment needed to take this technology commercial?

To achieve large coal volume processing means entering new markets with a less-expensive and much larger scale processing facility. This would require about \$3.8 million in R&D costs and a new plant with a cost of \$37 million. These large-scale plants would likely be located on coal mine properties.

What major hurdles or barriers to next steps of development need to be addressed?

CFOAM, Ltd. and its largest customer, Touchstone Advanced Composites, are both growing rapidly, but are constrained by a lack of sufficient capital. Achieving meaningful sales in high volume, lower cost markets will require significant R&D (\$3.8 million) to elevate the process from a batch mode to a continuous mode.

Turning CO₂ Emissions into CO₂Concrete

CO₂Concrete, LLC - Gaurav Sant, Ph.D.

520 Broadway, 6th Floor, Santa Monica CA 90404 - (404) 775-6527 - gsant@co2concrete.com

MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☒ Building materials ☐ Life science applications ☐ Transportation fuels
☐ Other: _____

This technology uses CO₂ within flue gases to produce prefabricated concrete building materials and products. Unlike other approaches to CO₂ utilization, this technology can directly use flue gas streams with dilute CO₂ concentrations typical of emissions from coal-fired power plants and does not require an additional CO₂ capture or enrichment system. Further, the process requires little extrinsic heat inputs, as it can make use of low-grade heat in the flue gas. These key advantages enable unparalleled energy and CO₂ uptake efficiencies, and low CAPEX/OPEX relative to similar technologies for CO₂ utilization within construction materials. The process's use of abundant and economical material inputs, including hydrated lime and off-spec coal combustion wastes, ensures that it can produce construction products with price-equivalence to traditional concrete. The process can be used to produce prefabricated/precast concrete construction products (e.g., concrete blocks, bricks, beams, slabs) etc., which have large global markets. Today's global concrete industry has a market size of \$1 T with a projected growth rate of 5 – 6 % annually (over 20% of which is prefabricated concrete products). A majority of the market may be readily replaced by products that utilize CO₂. This potential market is projected to reach \$400 B by 2030.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☐ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☐ 50 to 100 ☒ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☐ Laboratory or bench formulation ☒ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☐ Commercial

To date, the largest scale demonstration has been a small pilot production facility located at the University of California, Los Angeles (UCLA). This system demonstrated the utilization of 200 kg CO₂ per day from simulated coal flue gas to produce concrete products. The system operated in over 10 production trials.

TIMING

Full commercial availability is feasible within:

- ☐ 1 year ☒ 3 years ☐ 5 years ☐ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☐Reduction of import dependence ☒Enhancement to international trade

☐Provides redundancy of sourcing ☐ Other: _____

ECONOMIC ☒Job creation ☒Economic support to region in downturn

☒Price advantage over alternative ☐ Other: _____

OTHER ☒Environmental improvement ☒Improved resource utilization

☐ Other: _____

The technology has the potential to have a positive impact on three industrial sectors within our economy: (1) retain jobs within the coal industry by offering end user (power industry) the ability to utilize coal-fired generation and greatly reduce CO₂ emissions, (2) utilize traditionally off-specification coal combustion residual, reducing corporate liabilities related to their management; (3) allow both utilities and independent power producers to meet their CO₂ emissions reduction targets and allows for the option to maintain their coal-fired generation; and, (4) create additional manufacturing jobs in the precast concrete industry through the integration of precast concrete plants with existing or new coal-fired generation.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

Approximately \$10.0M is required to take the technology from its current small pilot scale to a large pilot scale and demonstration level operations. The current strategy for demonstration projects includes integration and pilot operation at coal plants, which will begin in 2020 and carry on through 2022.

What is the magnitude and type of investment needed to take this technology commercial?

Taking the technology from multiple proven demonstrations at coal-fired power stations to full commercial operations will take approximately \$3.0M - \$5.0M for the core support activities required to achieve a strong commercial presence. This investment would cover technical support staff, marketing, sales and product development.

What major hurdles or barriers to next steps of development need to be addressed?

Taking into account the success of the technology at the small pilot scale, the major hurdle is obtaining the level of investment required to conduct a minimum of two large scale demonstrations of the technology. Design work for the next level of activity is already underway.

Technology Overview

Coal Fly Ash and CCR to Building Products

CTC Foundation | Howard McClintic

2711 Jefferson Davis Hwy, Suite 620, Arlington, VA 22202 | (202) 689-4586 | McClintH@CTC.com

MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☒ Building materials ☐ Life science applications ☐ Transportation fuels
☐ Other: _____

The Technologies International Corporation (TIC) high temperature process is very well suited for converting coal fly ash into salable rock wool fibers, used in making insulation, and the recovery of iron found in the ash. Unlike current manufacturers that use older cupola technology for melting, which is unsuitable for the high velocities of coal fly ash, the low gas velocities in the TIC furnace reactor minimize the amount of fly ash that could blow out of the furnace.

The rock wool market is a multibillion dollar one. The main raw materials for current rock wool manufacturers comes from blast furnace operations, which are closing.

Technologies International Corporation (TIC) uses an electric arc furnace (EAF) to achieve high temperatures, to transform waste streams (coal fly ash, e-waste, etc.) into useful, salable products.

TIC has been in existence for 10 years and holds 18 related patents. Organic materials are transformed into clean syngas. Inorganic materials turn to slag and float on top of recovered metals. Nearly \$9 million invested in TIC, including funding from NETL.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☐ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☒ 50 to 100 ☐ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☐ Laboratory or bench formulation ☒ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☐ Commercial

Tests have been done a number of times using a small pilot plant.

TIMING

Full commercial availability is feasible within:

- ☐ 1 year ☒ 3 years ☐ 5 years ☐ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☐ Reduction of import dependence ☒ Enhancement to international trade

☒ Provides redundancy of sourcing ☐ Other: _____

ECONOMIC ☒ Job creation ☒ Economic support to region in downturn

☒ Price advantage over alternative ☐ Other: _____

OTHER ☒ Environmental improvement ☒ Improved resource utilization

☐ Other: _____

The technology allows for the conversion of coal ash into rock wool fibers a valuable product for insulation, agriculture (for commercial seed growing and aquaponics) and fibers that have application in high strength concrete. The process will also recover the iron found in the ash while remediating a potential environmental issue due to leaching from the ash ponds. The process will allow existing power plants with a new disposal alternative for excess fly ash and thus provide work for coal miners and power plant employees. The treatment facility employment will depend on size but in a commercial system the plant employment will be between 100 to 200 workers per plant.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

The next stage is a pilot plant that can generate larger amounts of rock wool fiber that can be supplied to potential users for testing. The cost for this pilot will be \$7.4 million

What is the magnitude and type of investment needed to take this technology commercial?

The commercial sized plant cost will depend on the size of the unit. A system capable of processing about 20 tons per hour of coal ash will cost about \$45.7 million dollars.

What major hurdles or barriers to next steps of development need to be addressed? (50 words)

Acceptance of a new technology is the first barrier. Funding leadership is a second barrier. Narrow "vision" or sense of mission is a third barrier as utilities are reluctant to take risks even though the risks are advantageous for reducing an environmental issue and generating a revenue from what is currently an expense.

Technology Overview

Coal to Fullerenes and Nanotubes

CTC Foundation | Howard McClintic

2711 Jefferson Davis Hwy, Suite 620, Arlington, VA 22202 | (202) 689-4586 | McClintH@CTC.com

MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☐ Building materials ☐ Life science applications ☐ Transportation fuels
☒ Other: Carbon nanoparticles

A novel method for the formation of fullerenes and carbon nanotubes is to convert CO₂ in a very high temperature vessel. Technologies International Corporation (TIC) described this process in a U.S. Patent Office submission entitled "Method and Apparatus for Precipitation of Nano-structured Carbon Solids". The process described included the introduction of CO₂ into an AC plasma environment wherein the carbon becomes ionized and reforms into nano particles, mainly fullerenes and nanotubes. The particles are rapidly quenched to stabilize them. This process for making nano-particles is suitable in the formation of "Bucky paper".

TIC uses an electric arc furnace (EAF) to achieve high temperatures, to transform waste streams (coal fly ash, e-waste, etc.) into useful, salable products. TIC has been in existence for 10 years and holds 18 related patents. Organic materials are transformed into clean syngas. Inorganic materials turn to slag and float on top of recovered metals. TIC is the only thermal technology for extracting rare earth elements (REEs). Conventionally, chemicals are used. The system has zero air emissions. Nearly \$9 million invested in TIC, including funding from NETL.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☒ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☐ 50 to 100 ☐ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☒ Laboratory or bench formulation ☐ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☐ Commercial

Tests have been done a number of times using a 500 kW AC plasma system

TIMING

Full commercial availability is feasible within:

- ☐ 1 year ☒ 3 years ☐ 5 years ☐ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☐Reduction of import dependence ☐Enhancement to international trade

☒Provides redundancy of sourcing ☒ Other: Military and Aerospace

ECONOMIC ☒Job creation ☒Economic support to region in downturn

☒Price advantage over alternative ☐ Other: _____

OTHER ☒Environmental improvement ☐Improved resource utilization

☐ Other: _____

The technology allows for the conversion of CO₂ into fullerenes and nanotubes in large quantities at a very reduced cost. The system may also work for the formation of graphene, but work has not been done to confirm that carbon configuration. This process will convert CO₂ into desirable products that have many applications and are needed for research into new fields

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

The next stage is a pilot plant that can generate larger amounts of nanoparticles that can be supplied to potential users for testing. The cost for this pilot will be \$5.8 million

What is the magnitude and type of investment needed to take this technology commercial?

The commercial sized plant cost will depend on the size of the unit. Due to the unusual products being generated with this technology, a versatile system capable of producing nanoparticles in commercial quantities will cost about \$8 million dollars.

What major hurdles or barriers to next steps of development need to be addressed?

Acceptance of a new technology is the first barrier. Funding leadership is a second barrier. This technology is of great interest to other researchers that are investigating further applications of these products. Some of the national labs, like Oak Ridge, have expressed interest.

Technology Overview

Coal derived rare earth elements

CTC Foundation | Howard McClintic

2711 Jefferson Davis Hwy, Suite 620, Arlington, VA 22202 | (202) 689-4586 | McClintH@CTC.com

MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☒ Rare earth elements
☐ Sorbents ☐ Building materials ☐ Life science applications ☐ Transportation fuels
☐ Other: _____

A novel method for the recovery of REEs from coal or coal ash uses a modified arc furnace where the organics and inorganics in the coal and coal ash are reduced in a carbothermic process prior to being tapped leaving behind a misch metal containing the metals and REEs. These metals can then be conventionally processed or the metals can be recovered individually by sequential distillation and condensation. This process of carbothermic reduction was demonstrated to NETL in a prior contract and was found to be a success.

Technologies International Corporation (TIC) uses an electric arc furnace (EAF) to achieve high temperatures, to transform waste streams (coal fly ash, e-waste, etc.) into useful, salable products.

TIC has been in existence for 10 years and holds 18 related patents. Organic materials are transformed into clean syngas. Inorganic materials turn to slag and float on top of recovered metals. TIC is the only thermal technology for extracting rare earth elements (REEs). Conventionally, chemicals are used. The system has zero air emissions. Nearly \$9 million invested in TIC, including funding from NETL.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☐ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☒ 50 to 100 ☐ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☒ Laboratory or bench formulation ☐ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☐ Commercial

Tests were conducted in a bench scale for a NETL project to confirm the process which was deemed to be a success. Small pilot is being considered next.

TIMING

Full commercial availability is feasible within:

- ☐ 1 year ☐ 3 years ☒ 5 years ☐ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒Reduction of import dependence ☐Enhancement to international trade

☒Provides redundancy of sourcing ☐ Other: _____

ECONOMIC ☒Job creation ☒Economic support to region in downturn

☒Price advantage over alternative ☐ Other: _____

OTHER ☒Environmental improvement ☒Improved resource utilization

☐ Other: _____

The technology allows for the recovery of REEs from existing coal ash ponds from power plants and from new coal sources. The main sources of REEs currently are from China and this process will allow the U.S. to be self-sufficient and less reliant on foreign imports. The process will provide work for miners if new coal is being used and can remediate the environmental issues with current coal ash ponds that are leaching into the ground water table. The treatment facility employment will depend on size and whether it uses coal or an ash source, but in a commercial system the plant employment will be between 100 to 200 workers per plant. In addition, current coal mining employment can be maintained to supply the needed coal or coal ash. The recovered non-metallic slag will be non-leaching and pass TCLP tests.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

The next stage is a pilot plant that fully recovers individual REE's and fine tunes the process. The cost for this pilot will be \$6.5 million

What is the magnitude and type of investment needed to take this technology commercial?

The commercial sized plant cost will depend on the size of the unit. A system capable of processing about 20 tons per hour of coal ash will cost about \$45.7 million dollars.

What major hurdles or barriers to next steps of development need to be addressed?

Acceptance of a new technology is the first barrier. Funding leadership is a second barrier. Narrow "vision" or sense of mission is a third barrier as utilities are reluctant to take risks even though the risks are advantageous for national security by not relying on imported REEs

Technology Overview

Coal to Syngas for liquid fuels

CTC Foundation | Howard McClintic

2711 Jefferson Davis Hwy, Suite 620, Arlington, VA 22202 | (202) 689-4586 | McClintH@CTC.com

MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☐ Building materials ☐ Life science applications ☒ Transportation fuels
☐ Other: _____

Technologies International Corporation (TIC) uses an electric arc in a modified electric arc furnace (EAF), operating at 1760°C (3200°F), to gasify coal and create a syngas. This novel method has a very favorably energy mass balance as coal is completely converted into usable syngas — there are NO inherent losses. Conventional gasifiers combust a portion of the syngas to generate the reaction. This unique EAF process produces an unusually pure syngas with minimum contaminants and thus is ideal for liquid fuel formation. The system allows for steam reformation within the furnace to increase the amount of hydrogen.

TIC use of an electric arc furnace (EAF) to achieve high temperatures transforms diverse waste streams (coal fly ash, e-waste, MSW, etc.) into useful, salable products. TIC has been in existence for 10 years and holds 18 related patents. Organic materials are transformed into clean syngas. Inorganic materials turn to slag and float on top of recovered metals. TIC is the only thermal technology for extracting rare earth elements (REEs). Conventionally, chemicals are used. The system has zero air emissions. Nearly \$9 million invested in TIC, including funding from NETL.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☒ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☒ 50 to 100 ☐ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☐ Laboratory or bench formulation ☒ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☐ Commercial

Tests have been done a number of times using different types of coal. The process allowed the use of high sulfur coal and tests were done with lignite, metallurgical coal and anthracite. All except the lignite had steam injection to get the right syngas chemistry.

TIMING

Full commercial availability is feasible within:

- ☐ 1 year ☒ 3 years ☐ 5 years ☐ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒Reduction of import dependence ☐Enhancement to international trade

☒Provides redundancy of sourcing ☐ Other: _____

ECONOMIC ☒Job creation ☒Economic support to region in downturn

☒Price advantage over alternative ☐ Other: _____

OTHER ☒Environmental improvement ☒Improved resource utilization

☐ Other: _____

The technology allows for the conversion of coal into a very clean syngas that has multiple applications, from liquid fuels to chemicals. The ability to steam reform in the reactor/furnace as the coal is being gasified provides an increase level of control while reducing capital costs. This is a flexible gasifier where the system controls can adapt and accept coals with different characteristics without requiring equipment modifications. The coal does not have to be pulverized.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

The next stage is a pilot plant that can generate larger amounts of syngas that can be tested for different applications, both and chemicals supplied to potential users for testing. The cost for this pilot will be \$6.4 million

What is the magnitude and type of investment needed to take this technology commercial?

The commercial sized plant cost will depend on the size of the unit. A typical plant gasifying 20 tons per hour of coal will cost about \$42 Million.

What major hurdles or barriers to next steps of development need to be addressed?

Acceptance of a new technology is the first barrier. Funding leadership is a second barrier. The reduced cost of natural gas oil at this time has diminished investors' interest in this technology even though the costs are still below market.

Technology Overview

Pyrolysis of coal

Gen2, LLC - Gen Tech PTD, LLC - Kim Johnson

2000 S. Ocean Blvd #703, Delray Beach, FL 33483 - 816 728 3533 - k.johnson@gen2wte.com

MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☐ Building materials ☐ Life science applications ☒ Transportation fuels
☐ Other: _____

The technology within this sector includes several processes which fall broadly into liquefaction and gasification followed by an additional process to convert the liquid or syngas to a fuel or chemical. . Liquefaction may be direct liquefaction where a liquid is made in a single step through either pyrolysis, carbonisation, or direct hydrogen liquefaction. In addition to the process listed below, the direct liquid can be converted to diesel, naphtha and heavy fuel oil via high pressure hydrocracking and distillation. Indirect liquefaction includes processes whereby a synthetic gas is made in one process followed by conversion of this syngas into synthetic crude through: Fischer Tropes and further refining into fuels, methanol production, dimethyl ether production, and/or subsequent gasoline production. Other process options include the conversion of the formed syngas into a methane rich gas or SNG, or to separate the Hydrogen from the Carbon monoxide and other gases by means of membrane separation technology.

Market size:

The market size for direct liquefaction of bituminous coal to coal tar and subsequent diesel production could be as high as 146.33 million bbl/year (6145 million Gal/year) based on 46 % of U.S. coal production being attributed to bituminous coal and a coal to tar conversion of 10% and a conversion of coal tar to diesel of 60 %.

The technology can also be used to convert coal fines or waste coal to fuels.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☐ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☐ 50 to 100 ☒ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☒ Laboratory or bench formulation ☐ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☐ Commercial

Testing has been done on a small scale unit of 5 kg/hr in a Technotherm, an owner of Gen Tech PTD, pilot reactor in S. Africa. Upgrading of coal tars to diesel can be done in traditional hydrocracking processes which have widespread commercial use. FT of syngas produced from coal pyrolysis can be done using various FT processes available on the market.

TIMING

Full commercial availability is feasible within:

- ☐ 1 year ☒ 3 years ☐ 5 years ☐ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒Reduction of import dependence ☒Enhancement to international trade

☒Provides redundancy of sourcing ☐ Other: _____

ECONOMIC ☒Job creation ☒Economic support to region in downturn

☐Price advantage over alternative ☐ Other: _____

OTHER ☐Environmental improvement ☐Improved resource utilization

☐ Other: _____

The U.S. imports 10.14 million bbl/day of petroleum (crude and other hydrocarbons) conversion of coal to liquids could replace these imports.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

To go from a lab scale to a small pilot system, the technology required to convert bituminous coal to coal tar would be 1.8 million U.S.\$ for a 1.102 U.S. ton/hour facility which would output 0.1102 U.S. ton/hour of coal tar. The same investment of 1.8 million US\$ would be required for a facility processing 1.102 U.S. ton/hour of coal to 0.55 U.S. ton/hour of syngas.

The refinery required to convert the coal tar to diesel, naphtha and residue would be similar to a traditional hydrotreating circuit involving hydrodemetalation, hydro-desulphurisation, hydrocracking followed by distillation of the products. A 3 reactor setup will cost around 9 million US\$ for 1000 BPD throughput of coal tar.

The investment required for the FT route is estimated at 1.16 million US\$ using 0.55 U.S. ton/hour syngas based off of 10 MBTU syngas/bbl syncrude and 65 000 US\$/Daily barrel. This will output 17.5 bbl/day syncrude, of which 12.5 bbl/day is diesel, and 5.35 bbl/day is Naphtha.

What is the magnitude and type of investment needed to take this technology commercial?

Commercial stage for the technology require to convert bituminous coal to coal tar would be 3 million U.S.\$ for a 1.102 U.S. ton/hour facility which would output 0.1102 U.S. ton/hour of coal tar.

The refinery required to convert the coal tar to diesel, naphtha and residue would be similar to a traditional hydrotreating circuit involving hydrodemetalation, hydrodesulfurisation, hydrocracking followed by distillation of the products.

What major hurdles or barriers to next steps of development need to be addressed?

Extended testing needs to be done on bituminous coals specific to the U.S. and of consistent quality to give further proof of concept. This can be done by continuous pilot operation in the U.S. or by sending samples abroad for testing. Laboratory and pilot testing needs to be done on coal tar hydrotreating to diesel although this has been demonstrated at lab and pilot scale abroad.

Technology Overview

DryFining™

Great River Energy | Sandra Broekema

12300 Elm Creek Blvd., Maple Grove, MN 55369-4718 | (763)445-5304 | sbroekema@GREnergy.com

MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☐ Building materials ☐ Life science applications ☒ Transportation fuels
☒ Other: Coal Beneficiation - Lignite and Sub-bituminous

Simultaneous drying and density separation of sulfur and mercury compounds in a pre-combustion or gasification process; 55 Mt of coal beneficiated since 2009.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☐ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☒ 50 to 100 ☐ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☐ Laboratory or bench formulation ☐ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☒ Commercial

1,000 ton/hr at a 1200 MW electric generating station since late 2009.
DOE CCPI project for Prototype in 2007

TIMING

Full commercial availability is feasible within:

- ☒ 1 year ☐ 3 years ☐ 5 years ☐ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☐ Reduction of import dependence ☒ Enhancement to international trade

☐ Provides redundancy of sourcing ☐ Other:

ECONOMIC ☐ Job creation ☒ Economic support to region in downturn

☒ Price advantage over alternative ☐ Other:

OTHER ☒ Environmental improvement ☒ Improved resource utilization

☒ Other: ____ Plant efficiency

improvement _____

3% to 5% Plant efficiency improvement potential. SO₂, NO_x, Hg and CO₂ reduction potentials dependent on fuel and thermal head availability

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

NA

What is the magnitude and type of investment needed to take this technology commercial?

What major hurdles or barriers to next steps of development need to be addressed?

Likely \$1 to \$2 in overall cost per ton for the benefits enjoyed

Technology is commercial

Technology Overview

Coal Ash to Mineral Fiber

Green Coal Solutions, LLC, Mr. Ato B. Andoh, CEO

13001 Summit School Rd, Suite 4, Woodbridge, VA, 22192

(833)-COAL-ASH ext. 0, or 703-910-4022 | INFO@greencoalsolutions.com

MARKET SECTOR AND SIZE

- ☒ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☒ Building materials ☐ Life science applications ☐ Transportation fuels
☒ Other: Mineral Fiber, Paper Pulp, Insulation fibers, Textiles, Coal Emissions Capture Technology

Ability to convert all types of coal ash into a non-toxic, non-cancerous mineral fiber for use in multiple end-products that include:

MARKET SECTOR	GLOBAL MARKET SIZE IN USD 2016/2017
• Paper & Paper Products	~81.8 Billion
• Ceramic Fiber / Construction & Machine Insulation	~41 Billion
• Textiles	~1.237 Trillion
• Carbon Fiber Pre-Curser	~2.859 Billion
• Plastics	~321.4 Billion
• Rubber	~18.1 Trillion

As we consume coal in our recycling/manufacturing technology we utilize a secondary emissions capture technology that is capable of capturing 96-98% of coal power plant emissions (CO₂, SO₂, N₂O, mercury (HG)). Additionally, capable resulting from the emissions capture process of converting emissions into Synthetic Natural Gas.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☐ 1 to 10 ☐ 10 to 25 ☒ 25 to 50 ☐ 50 to 100 ☐ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☐ Laboratory or bench formulation ☐ Small pilot
☐ Large pilot ☒ First-of-a-kind demonstration at full scale ☐ Commercial

24,000 tons/year capacity mineral fiber plant successfully demonstrates the conversion of coal ash into high grade mineral fiber. Independent lab confirmed product safety and quality properties. Each production plant is scalable to convert/recycle up to 1 million tons of coal ash per year while directly employing over 200 personnel per factory. Consumption of nearly 15K Tons of Coal Ash

TIMING

Full commercial availability is feasible within:

- ☒ 1 year ☐ 3 years ☐ 5 years ☐ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒Reduction of import dependence ☒Enhancement to international trade ☐Provides redundancy of sourcing ☐ Other:

ECONOMIC ☒Job creation ☒Economic support to region in downturn
☒Price advantage over alternative ☐ Other:

OTHER ☒Environmental improvement ☒Improved resource utilization

NATIONAL SECURITY:

- Establishes the U.S. as the #1 producer of mineral fiber in the world
- Increase exports and ability to meet market demands for mineral fiber insulation and other downstream products manufactured from mineral or wood fiber.

ECONOMIC

- Over 200 direct jobs per a standard 1 MM Ton/year capacity facility & unspecified downstream jobs
- Downstream market stimulation – Textiles, Carbon Fiber, Plastics, Rubber, Construction, Cement & Piping industries, Friction Materials, Aviation & Space, Sound Proofing, Automotive
- Flexible production capability to respond to economic fluctuations and product demands by producing any one of ten product lines
- Significantly lower cost of production over fiberglass and other mineral fiber (Rockwool Fibers)

OTHER:

- Increased regional economic activity through the consumption of other materials
- Ecologically sound alternative for the production of paper, plastics, rubber, and construction materials
- Above industry standards in the reduction of greenhouse gases generated by the usage of coal fuel
- Provide affordable composite / carbon fiber production material for the marine, automotive, and aerospace industries to be used in commercial and defense applications
- Eliminate the need for long-term coal ash storage by power plants and state/local governments
- Comprehensive / scalable / permanent solution to clean up existing coal ash ponds/landfills

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

Between 22 to 44 acres of industrial zoned land, 25-60 megawatts of power, access to rail, and close proximity to coal ash (Power Generation Plant) or Coal Ash deposits. Ability to utilize existing industrial facilities (brownfields) as production plants, where available.

What is the magnitude and type of investment needed to take this technology commercial?

Between \$21-\$155M investment needed to stand up a full scale facilities that can recycle a range of 100,000 tons to 1M tons of coal ash per year into equal amounts of top-grade mineral fiber. With adequate funding, a single factory takes 8-14 months to get operational depending on site needs.

What major hurdles or barriers to next steps of development need to be addressed?

Availability of investment capital.

Technology Overview

Wave Liquefaction™

H Quest Vanguard, Inc. | George Skoptsov

750 William Pitt Way Pittsburgh, PA 15238 | 412.444.7008 | gls@h-quest.com

MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☐ Building materials ☐ Life science applications ☐ Transportation fuels
☒ Other: Battery-grade and industrial graphite

Wave Liquefaction™ technology (WL™) is an enhanced direct coal-to-liquids (DCL) process that uses non-thermal electromagnetic discharge to directly convert coal and methane into refinable oil (~10 API). Development of the technology targets a wide range of applications and scales of deployment. In particular, the process has been shown to produce coal liquids analogous to coal tar – aromatic liquids that are a by-product of coking – at 10x yields of conventional coking and with significant reduction of scale and capital cost requirements. Coal tar is an established source of chemicals and carbon materials, for example needle coke and battery-grade and electrode graphite. However, as the legacy coking plants are closing, the sources of coal tar continue to decrease world-wide.

From 30 M to 125 M electric vehicles are predicted to be sold by 2030. As much as 50kg-100kg of graphite is required per electric vehicle battery, translating into demand of 1.5M to 12.5M tons of graphite for the electric vehicles alone. Assuming 5% yield of battery graphite from a ton of coal, 30M to 250M tons of coal could be utilized as a source of this strategic material over the next decade.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☐ 1 to 10 ☐ 10 to 25 ☒ 25 to 50 ☐ 50 to 100 ☐ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☒ Laboratory or bench formulation ☐ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☐ Commercial

Wave Liquefaction™ has been demonstrated in a continuous laboratory-scale pilot system, capable of converting 3 kg/hour with a wide range of coals. The resulting liquids have undergone extensive characterization including GC/MS, elemental, NMR-13C analysis, and simulated distillation, which indicate low impurities, (especially quinoline insolubles), and high suitability for coking and

TIMING

Full commercial availability is feasible within:

- ☐ 1 year ☒ 3 years ☐ 5 years ☐ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒Reduction of import dependence ☒Enhancement to international trade ☒Provides redundancy of sourcing ☒ Other:

ECONOMIC ☒Job creation ☒Economic support to region in downturn

☒Price advantage over alternative ☐ Other: _____

OTHER ☒Environmental improvement ☒Improved resource utilization

Growth in U.S. sales of electric vehicles has been hindered by the high cost of the lithium-ion batteries used to power many electric vehicles (more than 50% of the vehicle cost). Currently, synthetic graphite is used in the anode of most lithium-ion batteries. Companies prefer using it because the consistency, quality, and properties of high-end synthetic graphite can be controlled during the manufacturing process, despite its cost being 2–10 times that of natural graphite. Natural flake graphite may serve only to supplement synthetic graphite and is limited in quantity and occurrence: China dominates production with 68% of the world's output, while there are no operational mines in the United States.

Wave Liquefaction™ may open nation's vast coal resources as a new source of graphite. It will secure supply of this strategic material, create new demand for coal, benefit environment through supporting electrification of mass transport and provide a cleaner and cheaper method of synthetic graphite production. A single 1,500 – 15,000 ton/year synthetic graphite plant would create a new demand for 30-300 thousand tons of coal. Situated in coal regions impacted by the downturn in coal production, each plant would create ~50 permanent, high-skilled jobs where they are needed most, and 4-5 times as many indirect jobs.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

To advance to a pilot plant stage, the current lab-scale system must be upgraded to support continuous conversion of coal at the rate of 10-20 kg/hour, to demonstrate viability of the technology. The resulting liquids will be graphitized using conventional methods. Resulting graphite will be evaluated in the final applications such as Li-ion battery. The full cost of a 3-year effort culminating in a standalone commercial plant producing 1500 tons of synthetic graphite per year (\$30M/year revenue) would be \$30M dollars.

What is the magnitude and type of investment needed to take this technology commercial?

Once the process has been proven at pilot scale, scale-up by unit replication will allow fast deployment at commercial scale. Assuming 5% yield of graphite (battery-grade or needle coke for electrodes) from raw coal, a single full-scale reactor plant would support production of 1500 tons of graphite per year (\$30M in revenue) consuming 30,000 tons of coal. A single-reactor fully commercial plant could be deployed within 3 years for ~\$30M. A \$300M revenue plant (10 reactors) could be deployed for only \$50M.

What major hurdles or barriers to next steps of development need to be addressed?

Major development hurdles are reactor scale-up and testing with adequate balance of plant system. One-step scale-up minimizes costs and risk: once reactor operation is proven at the next (industrial) scale, further scale-up will be accomplished only through unit replication. Graphite would be produced via conventional, well-established methods, and would be confirmed as acceptable to industrial consumers early in the program.

Wave Liquefaction™

H Quest Vanguard, Inc. | George Skoptsov

| 750 William Pitt Way Pittsburgh, PA 15238 | 412.444.7008 | gls@h-quest.com

MARKET SECTOR AND SIZE

- ☒ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☐ Building materials ☐ Life science applications ☐ Transportation fuels

Wave Liquefaction™ technology (WL™) is an enhanced direct coal-to-liquids (DCL) process that uses non-thermal electromagnetic discharge to directly convert coal and methane into refinable oil (~10 API). Development of the technology targets a wide range of applications and scales of deployment. In particular, the process has been shown to produce coal liquids analogous to coal tar – aromatic liquids that are a by-product of coking – at 10x yields of conventional coking and with significant reduction of scale and capital cost requirements. Coal tar is an established source of chemicals and carbon materials, for example high-stiffness graphitic carbon fiber. However, as the legacy coking plants are closing, the sources of coal tar continue to decrease world-wide.

Pitch-based carbon fibers have exceptional properties compared to the commonly used PAN-fibers. They are distinguished by high mechanical stiffness (high modulus), have high heat and electric conductivity, have near zero coefficient of thermal expansion, and a high degree of dimensional stability. These carbon fibers have been widely used in Japan for seismic reinforcement and repair of concrete structures, and have been piloted in the United States for non-disruptive reinforcement of concrete overpasses. Reduction of cost for the high modulus fibers would spur explosive growth of use in construction and civil engineering, allowing reduction in use of steel and concrete for new construction, and non-intrusive repairs in reinforcement projects. As the carbon fiber does not corrode, cost-effective carbon laminate reinforcement would be an attractive alternative to costly capital repairs or bridge replacement. Chopped fibers are widely used as an additive to plastics to improve their thermal conductivity and, at a lower price point, would be an attractive addition to thermoset plastics with applications in vehicle lightweighting.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☐ 1 to 10 ☐ 10 to 25 ☒ 25 to 50 ☐ 50 to 100 ☐ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☒ Laboratory or bench formulation ☐ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☐ Commercial

Wave Liquefaction™ has been demonstrated in a continuous laboratory-scale pilot system, capable of converting 3 kg/hour with a wide range of coals. The resulting liquids have undergone extensive characterization including GC/MS, elemental, NMR-13C analysis, and simulated distillation, which indicate low impurities, (especially quinoline insolubles), and high suitability for pitch processing, spinning, and graphitization.

TIMING

Full commercial availability is feasible within:

- ☐ 1 year ☐ 3 years ☒ 5 years ☐ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒Reduction of import dependence ☒Enhancement to international trade ☒Provides redundancy of sourcing ☒ Other:

ECONOMIC ☒Job creation ☒Economic support to region in downturn

☒Price advantage over alternative ☐ Other: _____

OTHER ☒Environmental improvement ☒Improved resource utilization

The main hurdle to pervasive adoption of carbon fiber and carbon-based composites in construction and automotive industries is the high cost of production. Cost of precursor (polyacrylonitrile accounts for more than 90% of carbon fiber produced worldwide) exceeds \$3/kg and accounts for as much as 50% of the lowest grade carbon fiber manufacturing costs.

Coal tar pitch is an attractive alternative feedstock for carbon fiber production. Pitch-based carbon fibers generally have higher stiffness and thermal conductivities, which make them particularly useful in thermal management application and for uses demanding high dimensional stability. Pitch-based carbon fibers are a lot less common, with price levels one to two orders of magnitude higher than for regular (PAN-based) carbon fiber. They have traditionally been used for the most demanding applications, such as satellite structures and space radiators, but they have also gained acceptance in high-end sports and industrial applications in spite of their high cost.

Wave Liquefaction™ may open nation's vast coal resources as a new source of graphitic carbon fiber. It will significantly lower the costs of this material, opening vast vehicle light weighting and construction markets, hence resulting in new demand for coal. It would benefit environment through reduction in GHG and energy-intensive cement and steel production, and provide a cleaner and cheaper source of carbon fiber precursor. Situated in coal regions impacted by the downturn in coal production, each 1,000 m.t./year plant would create 60-80 permanent, high-skilled jobs where they are needed most, 4-5 times as many indirect jobs.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

To advance to a pilot plant stage, the current lab-scale system must be upgraded to support continuous conversion of coal into liquids at the rate of 10-20 kg/hr, to demonstrate viability of the technology. The resulting liquids will be processed, spun, and graphitized using conventional methods, targeting stiff short fiber. Resulting fiber will be evaluated in the final applications such as thermoset plastics and concrete reinforcement. The full cost of a 3-year effort culminating in a standalone pilot processing 1.5 tons coal per hour would be \$25M dollars.

What is the magnitude and type of investment needed to take this technology commercial?

Once the process has been proven at pilot scale, scale-up by unit replication will allow fast deployment at commercial scale (12,000 m.t. / year nameplate capacity). A 10 reactor plant could be deployed for \$50M-\$85M, depending on complexity and cost of the carbon fiber manufacturing equipment.

Major development hurdles are reactor scale-up and testing with adequate balance of plant system. One-step scale-up minimizes costs and risk: once reactor operation is proven at the next (industrial) scale, further scale-up will be accomplished only through unit replication. Carbon fiber would be produced via conventional, well-established methods, and would be confirmed as acceptable to industrial consumers early in the program through a partnership with Oak Ridge National Lab.

What major hurdles or barriers to next steps of development need to be addressed?

Technology Overview

Wave Liquefaction™

H Quest Vanguard, Inc. | George Skoptsov

750 William Pitt Way Pittsburgh, PA 15238 | 412.444.7008 | gls@h-quest.com

MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☐ Building materials ☐ Life science applications Transportation fuels
☒ Other: Industrial Chemicals

Today, benzene and other monoaromatics (BTEX) are the crude oil-derived platform chemicals at the base of many important industrial supply chains: plastics, rubbers, fabrics, solvents, detergents, dyes, and pharmaceuticals. Benzene market for chemical use alone is 50 million tons worldwide. However, the domestic benzene deficit is expected to grow from 1.8 million tons in 2014 to 4.4 million tons by 2023, due to impact of the shale revolution on domestic BTEX sources.

A viable alternative method for production of coal-derived platform chemicals is direct, thermal conversion (pyrolysis) of coal. Destructive distillation of coal yields hydrocarbon gases, liquids (monoaromatics and coal tar), and coke. Until 1950s, the coke ovens were responsible for virtually 100% of the domestic benzene supply.

H Quest has developed and demonstrated a novel coal conversion process that avoids heat transfer and scale requirements limitations of conventional coal conversion technologies, and is well-suited for small-scale, distributed production of chemicals and material precursors from coal. Rapid (< 1 sec) pyrolysis of coal releases liquid products and intermediates into the relatively cool process gas, where immediate quenching prevents secondary cracking reactions. The result are the high yields of the relatively high-value liquids (50-60wt%, d.a.f), with a large BTEX fraction, and minimal yields of the low-value gases < 5wt%).

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☐ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☒ 50 to 100 ☐ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☒ Laboratory or bench formulation ☐ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☐ Commercial

Wave Liquefaction™ has been demonstrated in a continuous laboratory-scale pilot system, capable of converting 3 kg/hour. The resulting liquids have undergone extensive characterization including GC/MS, elemental, NMR-13C analysis, and simulated distillation, which indicate higher API, lower aromaticity, low asphaltene, higher paraffinic, and higher hydrogen contents than conventional coal liquids. In particular, monoaromatics can range in the 10%-30% of the liquid product.

TIMING

Full commercial availability is feasible within:

- ☐ 1 year ☐ 3 years ☒ 5 years ☐ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒Reduction of import dependence ☒Enhancement to international trade ☒Provides redundancy of sourcing ☒ Other:

ECONOMIC ☒Job creation ☒Economic support to region in downturn

☒Price advantage over alternative ☐ Other:

OTHER ☒Environmental improvement ☒Improved resource utilization

Producing 5 million tons of coal-derived BTEX per year would require production of 25M-50M tons of coal-derived oil per year and create new demand for 50M-100M tons of coal per year. This scale require deployment of a 40-80 small 100K bpd Wave Liquefaction™ plants across the nation's coal basins, each creating ~80 permanent, high-skilled jobs where they are needed most and contributing to creation of at least 300 indirect jobs. Coal-derived oil and chemicals produced with up to 80% lower lifecycle GHG emissions than the conventional petroleum refining would not only improve energy security by reducing reliance on foreign oil, but would also strongly contribute to the nation's net oil exports and improve competitiveness of the domestic chemical industry through lower prices and higher availability of the petrochemical feedstocks.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

To advance to a pilot plant stage, a project delivering gallon/barrel quantities of fuels, techno-economic and life-cycle analyses, and a detailed system design package is needed. The full cost of a 3-year effort culminating in a standalone pilot plant is \$20M dollars.

What is the magnitude and type of investment needed to take this technology commercial?

Once the process has been proven at pilot scale, scale-up by unit replication will allow fast deployment at commercial scale (within 5-7 years). A 100 kbpd fuels plant co-producing 125-250 thousand tons of BTEX per year would cost \$150M-\$200M depending on the type of coal and final product requirements.

What major hurdles or barriers to next steps of development need to be addressed?

Major development hurdles are reactor scale-up and testing with adequate balance of plant system. One-step scale-up minimizes costs and risk: once reactor operation is proven at the next (industrial) scale, further scale-up will be accomplished only through unit replication. Yields of products and energy requirements have to be demonstrated at scale for each addressed coal.

Technology Overview

Wave Liquefaction™

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MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☐ Building materials ☐ Life science applications ☐ Transportation fuels
☒ Other: Coal Beneficiation

Wave Liquefaction™ technology (WL™) is an enhanced direct coal-to-liquids (DCL) process that uses non-thermal electromagnetic discharge to directly convert coal and methane into refinable oil (~10 API). Originally developed under a DARPA JP8-from-coal study at the Pacific Northwest National Laboratory, the technology has been under development by H Quest Vanguard, Inc. in Pittsburgh, PA. Continuous oil production has been demonstrated on a wide range of coals, including Illinois #6 and Wyodak. Energy requirements reached as low as 350 kWh per barrel, liquid yields >60%, and gas yields <5% (weight, dry ash-free basis).

Coal beneficiation is a free side-effect of the liquefaction process, with yields of solid char starting at ~40% (wt%, d.a.f). The carbon-rich char product shows complete removal of moisture, translating into significant increase of heat contents compared to high-moisture parent coals such as Wyodak. Depending on specific configuration of the process, char can be completely devolatilized, further improving quality of the char as fuel. Alternatively, heavier liquid compounds may be retained in the char serving as intrinsic binder to ease pelletization and suppressing pyrophoricity of reactive coals such as Wyodak, hence improving their export profile (10% reduction in weight decreasing transportation costs and correspondingly higher heating value). U.S. exports 120 million tons of coal per year. For sulfur-rich coals such as IL#6 (~60Mt/year), Wave Liquefaction™ has been shown to decrease sulfur contents from 3%-6% in parent coal to < 1% in the char. Application of Wave Liquefaction at broad scales would double production of coal and while improving the solid fuel properties essentially free of charge.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☒ <1 ☐ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☐ 50 to 100 ☐ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☒ Laboratory or bench formulation ☐ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☐ Commercial

Wave Liquefaction™ has been demonstrated in a continuous laboratory-scale pilot system, capable of converting 3 kg/hour with a wide range of coals. The chars have undergone extensive characterization including elemental and proximate analyses, SEM, TEM and optical photography, which indicate decrease in S%, elimination of moisture, high porosity in raw char, and potential for retention of coal pitch as intrinsic binder agent and pyrophoricity suppressor.

TIMING

Full commercial availability is feasible within:

☐ 1 year ☐ 3 years ☐ 5 years ☒ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒ Reduction of import dependence ☒ Enhancement to international trade ☒ Provides redundancy of sourcing ☐ Other:

ECONOMIC ☒ Job creation ☒ Economic support to region in downturn
☒ Price advantage over alternative ☐ Other:

OTHER ☒ Environmental improvement ☒ Improved resource utilization
☐ Other: _____

Producing 10M barrels/day of coal-derived oil would require deployment of a 100 small 100K bpd Wave Liquefaction™ plants across the nation's coal basins, each creating ~80 permanent, high-skilled jobs where they are needed most and contributing to creation of at least 300 indirect jobs. These plants would create a new demand for 120M tons of coal per year while offering 50M-60M tons of cleaner burning beneficiated coal product with reduced sulfur, moisture, and volatile contents for domestic and export markets. Elimination of moisture would directly improve the electricity generation efficiency and environmental profile of the high-moisture coals such as Wyodak (> 165 billion recoverable tons), improve their export attractiveness, and reduce railroad transportation costs (48% of delivered cost of coal according to EIA) as well as its environmental impact.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

To advance to a pilot plant stage, a project delivering gallon/barrel quantities of fuels, techno-economic and life-cycle analyses, and a detailed system design package is needed. The full cost of a 3-year effort culminating in a standalone pilot plant processing 30-50 tons of coal per day is \$20M dollars.

What is the magnitude and type of investment needed to take this technology commercial?

Once the process has been proven at pilot scale, scale-up by unit replication will allow fast deployment at commercial scale (within 5-7 years) – 100 kbpd plant costing \$150M-\$200M depending on the type of coal and final product requirements.

What major hurdles or barriers to next steps of development need to be addressed? (50 words)

Major development hurdles are reactor scale-up and testing with adequate balance of plant system. One-step scale-up minimizes costs and risk: once reactor operation is proven at the next (industrial) scale, further scale-up will be accomplished only through unit replication. Value of the solid char product and suitability for coal replacement / augmentation will need to be established in collaboration with a coal power plant and coal vendors. Transportation safety of beneficiated (dried) coal will need to be established.

Technology Overview

Wave Liquefaction™

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MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☐ Building materials ☐ Life science applications ☒ Transportation fuels
☐ Other: _____

Wave Liquefaction™ technology (WL™) is an enhanced direct coal-to-liquids (DCL) process that uses non-thermal electromagnetic discharge to directly convert coal and methane into refinable oil (~10 API). Originally developed under a DARPA JP8-from-coal study at the Pacific Northwest National Laboratory, the technology has been under development by H Quest Vanguard, Inc. in Pittsburgh, PA. Continuous oil production has been demonstrated on a wide range of coals, with energy requirements reached as low as 350 kWh per barrel, liquid yields >60%, and gas yields <5% (weight, dry ash-free basis). The projected costs to produce JP-8 from Illinois #6 coal and methane (70% coal on HHV basis) are 25% lower than conventional petroleum production. CO₂ emissions and water consumption are estimated to be 80% lower than competing technologies, meeting or exceeding EISA 2007 §526 lifecycle greenhouse gas emissions requirements.

In 2014, the crude oil market worldwide exceeded \$3 trillion. Worldwide demand for petroleum is in excess of 90 million barrels/day and is projected (EIA 2016) to grow by 1.0% a year through 2040, mostly in the non-OECD countries. Outside of the Middle East, the new oil plays are primarily in unconventional oil: deep water, shale, tar sands, and gas/coal-to-liquids).

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☐ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☐ 50 to 100 ☒ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☒ Laboratory or bench formulation ☐ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☐ Commercial

Wave Liquefaction™ has been demonstrated in a continuous laboratory-scale pilot system, capable of converting 3 kg/hour. The resulting liquids have undergone extensive characterization including GC/MS, elemental, NMR-13C analysis, and simulated distillation, which indicate higher API, lower aromaticity, low asphaltene, higher paraffinic, and higher hydrogen contents than conventional coal liquids.

TIMING

Full commercial availability is feasible within:

- ☐ 1 year ☐ 3 years ☐ 5 years ☒ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒ Reduction of import dependence ☒ Enhancement to international trade ☒ Provides redundancy of sourcing ☐ Other:

ECONOMIC ☒ Job creation ☒ Economic support to region in downturn
 ☒ Price advantage over alternative ☐ Other

OTHER ☒ Environmental improvement ☒ Improved resource utilization
☒ Other: _____

Established unconventional oil sources, such as deep-water drilling, heavy oil sands, and shale oil, are capital intensive, have high costs of production (\$40-\$100 / barrel), and have a grave environmental impact. This opens an attractive window of opportunity for the nation's large, long-term coal reserves to be a new, dependable source of crude petroleum and fuels, which will not be hampered by well depletion or a requirement to continually invest in exploration and drilling.

Coal-derived oil produced with up to 80% lower lifecycle GHG emissions than the conventional petroleum would not only improve energy security by displacing 10M barrels/day imports of foreign oil, but also strongly contribute to oil exports, creating jobs across the United States, and strengthening the nation's coal industry. Producing 10M barrels/day would require deployment of a 100 small 100K bpd plants across the nation's coal basins, each creating ~80 permanent, high-skilled jobs where they are needed most and contributing to creation of at least 300 indirect jobs. These plants would create a new demand for 120M tons of coal per year.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

To advance to a pilot plant stage, a project delivering gallon/barrel quantities of fuels, techno-economic and life-cycle analyses, and a detailed system design package is needed. The full cost of a 3-year effort culminating in a standalone pilot plant producing 100 barrel/day of fuels or refinable oil is \$20M dollars.

What is the magnitude and type of investment needed to take this technology commercial?

Once the process has been proven at pilot scale, scale-up by unit replication will allow fast deployment at commercial scale (within 5-7 years). 100 kbpd plant would cost \$150M-\$200M depending on the type of coal and final product requirements -- an order of magnitude lower than conventional processes thanks to high throughput, mild conditions, and elimination of additional hydrogen (SMR) units.

What major hurdles or barriers to next steps of development need to be addressed?

Major development hurdles are reactor scale-up and testing with adequate balance of plant system. One-step scale-up minimizes costs and risk: once reactor operation is proven at the next (industrial) scale, further scale-up will be accomplished only through unit replication. Liquid products will be confirmed as acceptable transportation fuels early in the development program.

Technology Overview

Beneplus

LP Amina - William Latta, Founder and Director

2315 Randolph Road, #2, Charlotte, NC 28207 - Cell: (704) 877-6878 - Phone: (704) 280-8760

Fax: (704) 280-8761 - wlatta@lpamina.com - www.lpamina.com

MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☐ Building materials ☐ Life science applications ☒ Transportation fuels
☒ Other: __High value hydrocarbons and power generation__

BenePlus is a unique coal processing technology that upgrades coal and, in parallel, produces clean streams of high-value hydrocarbons, including a fuel gas, NGLs and Aromatics (Benzene, Toluene, Xylene). Simply put, BenePlus is to coal what oil refining is to crude oil, where it fractionates feedstock into various high-value products. The technology works on a wide range of coals including lignite, sub-bituminous and bituminous coals. Capital requirements for the technology are relatively modest, and multiple high-value outputs result in a projected simple payback of less than 3 years.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☐ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☐ 50 to 100 ☒ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☐ Laboratory or bench formulation ☒ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☐ Commercial

BenePlus was developed in partnership with Bayer Technology Services and the Southwest Research Institute over the past 5 years. A pilot plant was constructed and operated at SwRI since 2015. Based on pilot plant results, the technology is ready for development to commercial scale.

TIMING

Full commercial availability is feasible within:

- ☐ 1 year ☒ 3 years ☐ 5 years ☐ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒Reduction of import dependence ☒Enhancement to international trade

☒Provides redundancy of sourcing ☐ Other: _____

ECONOMIC ☐Job creation ☒Economic support to region in downturn

☒Price advantage over alternative ☐ Other: _____

OTHER ☒Environmental improvement ☒Improved resource utilization

☐ Other: _____

Technology Highlights

BenePlus is a revolutionary proprietary technology that converts raw coal into three value-added products

1. upgraded coal, PCI, carbon fiber / foam, activated carbon, etc. with various high value applications
2. liquid aromatics (Benzene, Toluene, Xylene (BTX)) for petrochemical feedstock and/or gasoline octane boosting
3. fuel gas to improve power generation efficiency by 50%

BenePlus also¹:

- reduces greenhouse gases
- removes 80% of mercury and 75% of sulfur from raw coal
- reduces up to 85% of power plant SOx air pollutants
- removes 95% of water from raw coal
- produces clean water for industrial use or potable use with additional purification
- improves power generation efficiency by 50% (using fuel gas produced)
- captures CO₂ for enhanced oil recovery or other applications

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

\$35M for large pilot.

What is the magnitude and type of investment needed to take this technology commercial?

\$100m for demonstration / semi-commercial

What major hurdles or barriers to next steps of development need to be addressed?

Funding.

Technology Overview

Carbide

LP Amina - William Latta, Founder and Director

2315 Randolph Road, #2, Charlotte, NC 28207 - Cell: (704) 877-6878 - Phone: (704) 280-8760

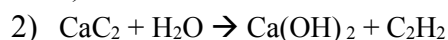
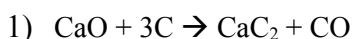
Fax: (704) 280-8761 - wlatta@lpamina.com - www.lpamina.com

MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☐ Building materials ☐ Life science applications ☒ Transportation fuels
☐ Other: _____

Alkali Carbides from coal is a disruptive coal technology for both chemical production and power generation by providing an easy route to commercially competitive acetylene production. Acetylene is a valuable intermediate compound used in the production of dozens of light and medium molecular weight organic compounds. Alkali carbides are stable solids that readily form acetylene when added to water. An example is calcium carbide:

Figure 1: Calcium Carbide Reaction



Rxn 1 is carried out at high temperatures (1800C) and forms the marketable product. The CO can also be used for power generation or chemical production. The CaC_2 produces acetylene, which is formed by hydrating the CaC_2 using Rxn 2. The lime can be used in Portland cement or recycled. The current state of the technology utilizes an electric arc furnace to achieve the high temperature conversion. LP Amina's development effort is to eliminate the need for the electric arc furnace through a carbothermic process or using an alternative alkali carbide reaction. The market size could be enormous at over 500m tons/year of coal utilization.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☐ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☐ 50 to 100 ☒ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☐ Laboratory or bench formulation ☐ Small pilot

In a joint US-China collaboration, a consortium of partners modified an existing 50 MWel tangential pulverized coal-fired boiler and retrofitted it based on the carbothermic process. The testing was not completed due to funding constraints.

- ☒ Large pilot ☐ First-of-a-kind demonstration at full scale ☐ Commercial

TIMING

Full commercial availability is feasible within:

- ☐ 1 year ☐ 3 years ☐ 5 years ☒ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒Reduction of import dependence ☒Enhancement to international trade

☒Provides redundancy of sourcing ☐ Other:

ECONOMIC ☒Job creation ☒Economic support to region in downturn

☒Price advantage over alternative ☐ Other:

OTHER ☒Environmental improvement ☒Improved resource utilization

☐ Other: _____

1. Reduce Oil Dependence: Nearly 3 million barrels of crude per day, or approximately 15% of U.S. oil consumption, is utilized by the chemical industry. Even a partial transition to domestic coal feedstock will significantly reduce U.S. dependency on foreign oil.

2. Improve Energy Efficiency: By combining chemical production with power generation, LP Amina's process is 50% more energy efficient than the conventional carbide process.

3. Create Jobs: The industry transition is poised to create tens of thousands of jobs across the value chain, from additional employment in engineering, to equipment manufacturing, construction, research and development, logistics, plant operations, etc. Companies and communities that adapt to this transition early will have the unique opportunity to build knowledge clusters and excellence centers to serve the rest of the industry.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

Grant funding of \$5m to develop a bench and small pilot in the US.

What is the magnitude and type of investment needed to take this technology commercial?

\$100M to develop a FOAK facility

What major hurdles or barriers to next steps of development need to be addressed?

In the large pilot demonstration, material issues were encountered that need to be resolved. A consortium would work to resolving these issues and build a new FOAK facility. An initial investment of \$5M USD is required to resolve the issues encountered in the FOAK facility.

Technology Overview

Recovery of Rare Earth Elements (REE) from Coal

Microbeam Technologies Incorporated | Steven A. Benson

4200 James Ray Drive, Ste 193, Grand Forks, ND 58202 | 701-213-

7070 | sbenson@microbeam.com

MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☒ Rare earth elements
☐ Sorbents ☐ Building materials ☐ Life science applications ☐ Transportation fuels
☐ Other: _____

Today the U.S. consumes about 16,000 tons/year of REE and is 100% dependent on imports for these important materials. Lignite from SW North Dakota has been shown to have significant amounts of weakly bound REE. A team led by the Institute for Energy Studies at UND has developed a process that is environmentally benign involving multiple extractions that results in a stream containing high levels of the valuable REE suitable for industrially proven processing methods that are extremely simple –resulting in fast time to market and low scale-up risks. For a single seam of lignite, the resource of recoverable REE is estimated to be between 1.8 and 3.7 million tons or enough to provide 100 to 200 years of U.S. supply. Multiple REE-rich seams exist. As an added benefit, the resulting coal product has been upgraded resulting in a “premium” boiler fuel. The development team led by the Institute for Energy Studies at UND includes Microbeam Technologies Inc., Barr Engineering, PNNL, and MLJ Consulting with funding support from the DOE’s NETL, North Dakota Industrial Commission, Great River Energy, North American Coal Company, Minnkota Power Cooperative, and Great Northern Properties. Collaborators include the North Dakota Geological Survey, ND University System, and Valley City State University.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☒ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☐ 50 to 100 ☐ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☒ Laboratory or bench formulation ☐ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☐ Commercial

The REE recovery process is environmentally benign and produces a REE-rich stream and a high purity lignite that can be utilized for power (as is currently occurring), chemicals, and other products. The process has been scaled up from a laboratory to a bench-scale. The bench-scale processes 5 to 10 kg/hr of coal. The next scale up will be at 0.25 to 0.5 ton/hour coal pilot plant.

TIMING

Please check one. Full commercial availability is feasible within:

- ☐ 1 year ☐ 3 years ☒ 5 years ☐ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒Reduction of import dependence ☐Enhancement to international trade

☐Provides redundancy of sourcing ☐ Other: _____

ECONOMIC ☐Job creation ☒Economic support to region in downturn

☐Price advantage over alternative ☐ Other: _____

OTHER ☐Environmental improvement ☒Improved resource utilization

☐ Other: _____

The REE recovery from lignite upstream of a 120 MW plant could produce up to 500 tons/year of REE. REE produced from a 120 MW plant for coals ranging from 300 to 600 ppm (dry coal basis) has the potential to \$180 to 360 million per year. The value of the REE is determined using average data from the U.S. DOE used in estimating REE value for coal (U.S. DOE, NETL – FOA, 2017). This does not include the cost of processing to separate and produce the pure individual REE.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

The pilot-scale at about 0.25-0.5 tph coal feed would require \$8 to 10 million. The investment would be from the U.S. Department of Energy and industry.

What is the magnitude and type of investment needed to take this technology commercial?

A small commercial demo at about 5-10 tph coal feed that would be ready for additional and larger (i.e. 50 tph) commercial projects would cost on the order of about \$20-25 Million. The source of investment would be from industry and U.S. DOE.

What major hurdles or barriers to next steps of development need to be addressed?

Funding for detailed characterization/mapping of the REE resource – drill coring in ND to obtain samples for analysis coordinated with the ND Geological Survey and building on considerable data already available.

Funding for scale-up, determination of overall economics, and opportunities to develop additional industries associated with REE (value chain from ore to products).

Technology Overview

NOVIHUM®

Novihum Technologies Inc. | Andre Moreira, CEO

150 Main Street, Suite 130, Salinas, CA 93901 | 855-NOVIHUM | a.moreira@novihum.com

MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☐ Building materials ☒ Life science applications ☐ Transportation fuels
☐ Other: _____

NOVIHUM® is produced by chemically modifying lignite to make a stable humus concentrate. Humus is the natural reservoir of high-grade stable organic matter that is the source of long-lasting fertility in naturally productive soils. It plays a critical role in soil function and health and takes many years to form under natural conditions.

Novihum Technologies has developed a chemical process that accelerates nature's work to produce top-quality humus in hours, using lignite as a raw material. When lignite is formed from decomposing plant material it undergoes chemical and biological processes that are very similar to those by which humus is formed. That makes it a rich source of the molecular building blocks of stable humus. However, over millions of years underground it loses critical elements – most especially nitrogen – and becomes less useful for plants. That is where Novihum Technologies steps in, with a new patented process that restores lignite's lost chemistry, transforming it into a concentrated carbon-rich granulate that is indistinguishable from the organic matter reservoirs found in nature's best soils.

Novihum Technologies estimates that between 25 and 50 million acres of agricultural land in North America would benefit from the application of NOVIHUM.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☐ 1 to 10 ☒ 10 to 25 ☐ 25 to 50 ☐ 50 to 100 ☐ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☐ Laboratory or bench formulation ☐ Small pilot
☐ Large pilot ☒ First-of-a-kind demonstration at full scale ☐ Commercial

NOVIHUM is currently produced at a demonstration plant (1,000 metric tons/year capacity) located in Dortmund, Germany and is sold directly to farmers and through specialty distributors in USA, Spain and Germany. Novihum Technologies plans to set up large-scale manufacturing capabilities in the USA within the next five years.

TIMING

Full commercial availability is feasible within: *please see NB below*

- ☐ 1 year ☐ 3 years ☒ 5 years ☐ 10 years ☐ >10 years

NB: Novihum Technologies is already registered and commercially available in some states (CA, AZ). The next stage is to build a manufacturing site in the USA (first step: ca. 30,000 tons/year).

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒ Reduction of import dependence ☐ Enhancement to international trade

☐ Provides redundancy of sourcing ☒ Other: *increased soil health and long-term food security*

ECONOMIC ☒ Job creation ☒ Economic support to region in downturn

☐ Price advantage over alternative ☐ Other:

OTHER ☒ Environmental improvement ☒ Improved resource utilization

☐ Other: _____

National Security: under current agricultural practices, soils often lose fertility and become less productive over time. With an increasing population and demand for high-value foods, it is paramount to protect access to good soils that can support food production now and for the long term.

Job creation & Economic support to region in downturn: Novihum Technologies' facility in the USA will be close to lignite-producing areas that are today economically depressed. A 30,000 tons production plant will create 20 long-term jobs and protect many more jobs in agriculture.

Environmental improvement: NOVIHUM greatly increases the health of soils and the plants that grow in them. It also contributes to CO2 emission reduction in agriculture (fertile soils require fewer inputs and produce more biomass).

Improved resource utilization: NOVIHUM unlocks the true value of lignite, transforming it into a high-value material for agriculture that enables farmers worldwide to grow better crops or even grow food in areas that were not previously suitable for agriculture.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

We expect to need investment of 15 to 20 million USD in order to build and operate a large-scale manufacturing site in the USA, starting with a plant size of ~30,000 tons/year.

What is the magnitude and type of investment needed to take this technology commercial?

The technology is already commercialized.

What major hurdles or barriers to next steps of development need to be addressed?

Low awareness of soil health. NOVIHUM is a new product in the market and is still convincing farmers and investors both that it works and that soil health solutions are worth investing in. There is a growing awareness among farmers and industry of the importance of soil health, and it is important for NOVIHUM that this trend continues.

Technology Overview

Coal Plastic Composites

Ohio University | Jason Trembly

259 Stocker Center Athens, OH 45701 | (740) 566-7046 | trembly@ohio.edu

MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☒ Building materials ☐ Life science applications ☐ Transportation fuels
☐ Other: _____

Coal plastic composite (CPC) materials are manufactured by mixing pulverized coal with thermoplastic resins and formed to various profiles based upon application. CPCs are an alternative to wood plastic composite (WPC) materials which have a host of applications in the construction, automotive, and electrical sectors. The first commercial CPC application being considered is decking materials. The composite decking sector is projected to undergo significant growth with 6 million tons per year of new demand by 2023.

CPC manufacturing requires minimal coal processing (pulverizing and drying), generates nearly zero emissions, and has been shown to possess better properties than WPC decking (flexure strength, fire properties, water absorption, lower costs). If successful, CPC manufacturing would create an additional 3 million tons per year of new coal demand.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☒ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☐ 50 to 100 ☐ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☐ Laboratory or bench formulation ☒ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☐ Commercial

To date, CPC materials are being manufactured using commercial pilot plant equipment.

TIMING

Full commercial availability is feasible within:

- ☐ 1 year ☒ 3 years ☐ 5 years ☐ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☐Reduction of import dependence ☐Enhancement to international trade

☐Provides redundancy of sourcing ☐ Other: _____

ECONOMIC ☒Job creation ☒Economic support to region in downturn

☒Price advantage over alternative ☐ Other: _____

OTHER ☒Environmental improvement ☒Improved resource utilization

☐ Other: _____

Benefits associated with CPC materials include: 1) coal product with minimal to no emissions, 2) lower cost decking product in comparison to WPCs, and 3) CPCs possess better burn properties, greater flexure strength, lower water absorption, and equivalent thermal expansion coefficients as WPCs allowing existing building methods to be used. Further, the team estimates that if CPCs would create 3 million tons per year of new coal demand this new industry would generate 2,000 new manufacturing jobs.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

Approximately \$250,000 in additional investment is necessary to conduct pilot-scale manufacturing of CPC boards and complete fire rating tests. Successful completion of these tests will demonstrate ability of CPCs to be used in decking applications.

What is the magnitude and type of investment needed to take this technology commercial?

Between \$1 to \$2 million in additional investment is necessary to scale and optimize CPC manufacturing and manufacture sufficient CPC boards to complete commercial qualification testing and offer initial CPC boards sales.

What major hurdles or barriers to next steps of development need to be addressed?

The next step in CPC development is to complete pilot-scale testing to manufacture sufficient quantity of boards to allow completion of fire testing. If CPC fire ratings are sufficient, the final steps to commercialization include optimizing CPC formulation and manufacturing processes and successfully completing qualification testing to allow commercial sale of CPC decking.

Technology Overview

Penncara Synpitch

Penncara Energy | James Swistock, President

| 283 River Drive, Tequesta, Florida 33469 | (814)883-1315 | jswistock@penncara.com

MARKET SECTOR AND SIZE

- ☒ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☐ Building materials ☐ Life science applications ☐ Transportation fuels
☒ Other: _Produces feedstock for carbon fibers and specialty graphite products, graphite furnace electrodes, needle and anode coke, and carbon electrodes for the silicon metal, aluminum, and ferroalloy production markets.

Pitch is the required feedstock for a variety of carbon products, and U.S. production of pitch derived from coal has been steadily disappearing. The Penncara Synpitch technology produces pitch from coal, using a direct extraction process, avoiding environmental issues associated with production from coal tar.

The U.S. currently produces less than 3% of global pitch production, and U.S. producers of carbon products are reliant on imports. Penncara Energy is developing U.S. production capacity, located in the U.S. coal fields, to supply a domestically-produced pitch with superior properties.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☒ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☐ 50 to 100 ☐ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☐ Laboratory or bench formulation ☒ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☐ Commercial

The technology was developed in the laboratory, tested at small pilot scale, and elements have been tested at large pilot scale.

TIMING

Full commercial availability is feasible within:

- ☐ 1 year ☒ 3 years ☐ 5 years ☐ 10 years ☐ <10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒ Reduction of import dependence ☐ Enhancement to international trade

☐ Provides redundancy of sourcing ☒ Other: Notably, reduction of import dependence for suppliers of carbon materials in the Department of Defense industrial base.

ECONOMIC ☒ Job creation ☒ Economic support to region in downturn

☐ Price advantage over alternative ☒ Other: Reduced feedstock requirements (over alternatives) for producers of carbon materials.

OTHER ☒ Environmental improvement ☒ Improved resource utilization

☐ Other:

The number of new manufacturing jobs related to this technology is in the range of 35 per plant installation. The availability of the materials will also help secure existing jobs in the U.S. mining and carbon materials manufacturing sectors.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

\$10 million, R&D investment

What is the magnitude and type of investment needed to take this technology commercial?

\$50 million, private placement(s)

What major hurdles or barriers to next steps of development need to be addressed?

Securing the required R&D funds, which will buy down risk associated with the first commercial installation.

Technology Overview

CCR-to-CCP

RamRock Building Systems, LLC | David White
2903 Braly Place, Chattanooga, TN 37415 | 423-314-3564

MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☒ Rare earth elements
☐ Sorbents ☒ Building materials ☐ Life science applications ☐ Transportation fuels
☒ Other: Activated carbon

The disposal of coal ash — properly, coal-combustion residuals (CCR) — has been ongoing for decades and has now reached some 2-3 billion tons contained in over 1,100 impoundments and landfills nationwide. In addition, over 100 million tons is produced annually and represent a large mineral resource and/or industrial waste stream.

RamRock uses proprietary, highly advanced, quantum computational chemistry and support processes to turn CCR into the line of CCR-based products (CCP).

High range estimates suggest the cleanup by the U.S. electric utility industry *may* cost it billions of dollars. Beyond the U.S., the rest of the world has hundreds of coal plants that are planned or already under construction.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☐ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☐ 50 to 100 ☒ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☐ Laboratory or bench formulation ☐ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☒ Commercial

Our foreign technology partner has commercialized advanced CCR utilization in projects including poured concrete buildings and foundations for wind farms, while proving out a line of related products from high-strength flowable fill for building and road bases to the roads themselves, along with consumer products like floor tiles, roof tiles, and pavers.

TIMING

Full commercial availability is feasible within:

- ☐ 1 year ☒ 3 years ☐ 5 years ☐ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒ Reduction of import dependence ☒ Enhancement to international trade

☒ Provides redundancy of sourcing ☒ Note: Rare earth elements only

ECONOMIC ☒ Job creation ☒ Economic support to region ☐ in downturn

☒ Price advantage over alternative ☐ Other:

OTHER ☒ Environmental improvement ☒ Improved resource utilization

☒ Other: Automation

We intend to turn conventional, single-purpose, coal-based power plants into large-scale, cutting-edge, eco-industrial parks, whereby coal isn't used solely for power generation but to manufacture commercial-grade products for sale into a wide variety of markets, thus having vastly more economic development impacts than they otherwise would, with vastly less environmental impact.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

We need \$2.5 million, over a three-year period, to conduct an at-scale demonstration project at one or another coal-fired power plant at one or another electric utility, supported by offsite laboratory R&D.

What major hurdles or barriers to next steps of development need to be addressed? (50 words)

Simple: finding an electric utility that has the vision to see what coal has to offer the world in the context described herein and the willingness to move mountains (of CCR) in order to make it happen.

Technology Overview

Direct Coal Hydrogenation Using the Veba-Combi Cracking Technology

Riverview Energy | Gregory Merle

6671 W. Indiantown Road, Ste. 50 #240, Jupiter, FL 33458

203-979-3993 | greg.merle@riverviewenergy.com

MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☐ Building materials ☐ Life science applications ☒ Transportation fuels
☐ Other: _____

To-date three commercial scale VCC Technology plants are operating – 2 in China and 1 in Russia. The first U.S. operating plant facility developed by Riverview Energy will utilize approximately 1.6 million metric tons per year of high sulfur coal.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☐ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☐ 50 to 100 ☒ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☐ Laboratory or bench formulation ☐ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☒ Commercial

The Direct Coal Hydrogenation process allows to transform coal into valuable and ultra-low sulfur transportation fuels. It is a chemical process that relies exclusively on temperature and pressure. The coal is neither burned or gasified insuring a carbon foot print much lower than coal gasification and Fisher-Tropsch processes. All by-products are marketable and there is no landfilling of ash. Both feedstocks – coal and natural gas – are abundant and cheap in the U.S. Including debt service, the break-even point is about \$47 per barrel of crude oil equivalent.

TIMING

Please check one. Full commercial availability is feasible within:

- ☐ 1 year ☒ 3 years ☐ 5 years ☐ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒ Reduction of import dependence ☐ Enhancement to international trade

☒ Provides redundancy of sourcing ☐ Other:

ECONOMIC ☒ Job creation ☐ Economic support to region in downturn

☒ Price advantage over alternative ☒ Other: Ultra-low sulfur diesel fuel

OTHER ☒ Environmental improvement ☒ Improved resource utilization

☒ Other: Production of low sulfur Naphtha as an additive for gasoline productions.

During the peak construction period, Riverview Energy will hire 2,500 construction work force. To operate the plant, it will require approximately 300 permanent employees.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

What is the magnitude and type of investment needed to take this technology commercial?

This selected VCC Technology based proposed plant will invest approximately \$2.5 billion to take it to operation.

What major hurdles or barriers to next steps of development need to be addressed?

Technology Overview

Coal to Liquid Fuels in Supercritical CO₂

Southern Illinois University Advanced Coal and Energy Research Center | William Hoback

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MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☐ Building materials ☐ Life science applications ☒ Transportation fuels
☐ Other: _____

Uses Fischer Tropsch Synthesis technology, but improves carbon utilization by nearly 3 fold and reduces GHG emissions by nearly 45 %. No refining required and can alter grade by blending with different fractions produced. Can compete with diesel and gasoline in end user markets.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☐ 1 to 10 ☐ 10 to 25 ☒ 25 to 50 ☐ 50 to 100 ☐ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☒ Laboratory or bench formulation ☐ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☐ Commercial

Have produced liquid fuels up to 160 mL/day in a 150 mL reactor.

TIMING

Full commercial availability is feasible within:

- ☐ 1 year ☐ 3 years ☐ 5 years ☒ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒ Reduction of import dependence ☐ Enhancement to international trade

☐ Provides redundancy of sourcing ☐ Other: _____

ECONOMIC ☒ Job creation ☐ Economic support to region in downturn

☐ Price advantage over alternative ☐ Other: _____

OTHER ☒ Environmental improvement ☒ Improved resource utilization

☐ Other: _____

Uses coal to produce petroleum based products.

Will create new jobs in coal rich regions.

Reduces GHG emissions by 45 % compared to traditional coal to liquid methods

Increases carbon utilization by 3 fold compared to traditional coal to liquid methods

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

\$600,000 to take it to produce 1 gal/day.

What is the magnitude and type of investment needed to take this technology commercial?

1.5 million to produce 30 gal/day.

What major hurdles or barriers to next steps of development need to be addressed?

Sensitivity of investment to oil prices is the major hurdle.

Technology Overview

Hybrid Nanofibers for Supercapacitors

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MARKET SECTOR AND SIZE

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☐ Sorbents ☐ Building materials ☐ Life science applications ☐ Transportation fuels
☒ Other: _____ Silicon Carbide, Alumina

Hybrid nanofiber containing heterogeneous mixed carbon nanofibers derived from coal, can be used to improve specific capacitance in a supercapacitor.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☐ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☐ 50 to 100 ☐ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☒ Laboratory or bench formulation ☐ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☐ Commercial

Clarify the scale in up to 50 words:

Concept has been proven and tested in a button cell.

TIMING

Full commercial availability is feasible within:

- ☐ 1 year ☒ 3 years ☐ 5 years ☐ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☐ Reduction of import dependence ☒ Enhancement to international trade

☐ Provides redundancy of sourcing ☒ Other: _Low cost high capacity storage_____

ECONOMIC ☒ Job creation ☐ Economic support to region in downturn

☒ Price advantage over alternative ☐ Other: _____

OTHER ☒ Environmental improvement ☒ Improved resource utilization

☐ Other: _____

Low cost materials with a higher specific capacitance produced. No environmental impact due to material degradation and supports renewable energy goals.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

\$1M and 3 years of research funding to take it to a pilot scale level.

What is the magnitude and type of investment needed to take this technology commercial?

Uncertain due to the nature of scale up of prototype. However, initial estimates suggest about 5-10 mil for commercializing this technology.

What major hurdles or barriers to next steps of development need to be addressed?

This technology needs high quality carbon nanofibers that can be generated from coal. The major hurdle is to be able to produce these nanotubes at a lower cost than what is currently available in the market.

Technology Overview

REE and Transition Metals from AMD sludge

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MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☒ Rare earth elements
☐ Sorbents ☐ Building materials ☐ Life science applications ☐ Transportation fuels
☒ Other: _____ Silicon Carbide, Alumina

Process produces separate streams of highly concentrated stream of rare earth elements and individual transition elements from acid mine drainage sludge.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☒ 1 to 10 ☒ 10 to 25 ☐ 25 to 50 ☐ 50 to 100 ☒ >100

LARGEST SCALE DEMONSTRATED

- ☒ None ☐ Laboratory or bench formulation ☐ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☐ Commercial

Concept has been devised and methods of extraction proven to work.

TIMING

Full commercial availability is feasible within:

- ☐ 1 year ☒ 3 years ☐ 5 years ☐ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒Reduction of import dependence ☐Enhancement to international trade

☐Provides redundancy of sourcing ☐ Other: _____

ECONOMIC ☒Job creation ☒Economic support to region in downturn

☒Price advantage over alternative ☐ Other: _____

OTHER ☒Environmental improvement ☒Improved resource utilization

☐ Other: _____

China dominates the world market in REE's. In 2017 alone, USA imported 150 million worth of rare earth compounds and metals, up from 118 million in 2016. Rare earths were not mined in 2017 in the United States. With Chinese tariffs of up to 25% on refined REE's, this import amount will be significantly higher in 2019.

Cost of extraction of REE's internally in the country, is expected to be lower than that from traditional sources since the fly ash and AMD sludge contain relatively high concentrations of REEs and certain transition metals of value. The treatment of the AMD sludge will reduce environmental and ecological issues associated with existing AMD ponds as well as create new sources of revenue.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

\$500,000 and 1 year of research funding

What is the magnitude and type of investment needed to take this technology commercial?

Government regulations and permit issues.

Success to form partners/obtain investment or other funding for initial resource evaluation.

What major hurdles or barriers to next steps of development need to be addressed?

Refining processes would utilize commercially available equipment. Process will need investors/partners in the form of raw material suppliers and venture capitalists along with matching government support.

Technology Overview

Coal to Carbon Nanotubes

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MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☐ Building materials ☐ Life science applications ☐ Transportation fuels
☒ Other: _____ Carbon
Nanotubes _____

The carbon nanotubes market is estimated to grow from USD 3.95 billion in 2017 to USD 9.84 billion by 2023, at a [CAGR of 16.70%] during the forecast period. Please refer to <https://www.marketsandmarkets.com/Market-Reports/carbon-nanotubes-139.html>

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☒ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☐ 50 to 100 ☐ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☒ Laboratory or bench formulation ☐ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☐ Commercial

TIMING

Full commercial availability is feasible within:

- ☐ 1 year ☒ 3 years ☐ 5 years ☐ 10 years ☐ >10 years
-

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒Reduction of import dependence ☒Enhancement to international trade

☐Provides redundancy of sourcing ☐ Other: _____

ECONOMIC ☒Job creation ☒Economic support to region in downturn

☒Price advantage over alternative ☐ Other: _____

OTHER ☒Environmental improvement ☒Improved resource utilization

☐ Other: _____

This technology once viable will allow very large scale production of carbon nanotubes (CNTs). CNTs already show a large application in several fields including high strength composite fillers, super capacitor battery materials, sorbents etc. So, it is anticipated that this will create large number of manufacturing jobs etc.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

A proper cost assessment needs to be done and the final output needs to be analyzed before answering this question.

What is the magnitude and type of investment needed to take this technology commercial?

Financial support for building large scale infrastructure as well as for recruiting expert man power for market/tech. analysis/risk assessment/ for production.

What major hurdles or barriers to next steps of development need to be addressed?

Inadequate financial support, appropriate collaboration with other (natural) industry partners/stake holders lacking,

Synfuels Americas

Fischer-Tropsch Synthesis Technology

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MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☐ Building materials ☐ Life science applications ☒ Transportation fuels

Synfuels Americas' parent company, Synfuels China Technology Company, Ltd. has developed and commercialized Fischer-Tropsch Synthesis technology for the production of liquid fuels and chemicals from coal. The technology is supported by Synfuels China's proprietary catalysts which are customized for each plant by the extensive Synfuels China team of scientists working in multiple hi tech laboratories throughout the globe. **The market for these products is substantial, and commercial adoption in the U.S. can result in a larger new market for U.S. coal.**

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☐ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☐ 50 to 100 ☒ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☐ Laboratory or bench formulation ☐ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☒ Commercial

TIMING

Full commercial availability is feasible within:

- ☒ 1 year ☐ 3 years ☐ 5 years ☐ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒ Reduction of import dependence ☒ Enhancement to international trade ☐ Provides redundancy of sourcing ☐ Other:

ECONOMIC ☒ Job creation ☒ Economic support to region in downturn ☒ Price advantage over alternative ☐ Other:

OTHER ☐ Environmental improvement ☒ Improved resource utilization ☐ Other: _____

The Chinese CTL plants use Synfuels China's proprietary Fischer-Tropsch synthesis process with medium temperature slurry-bed reactors as the process produces three times more C3+ hydrocarbon products per ton of catalyst than the industry average for conventional slurry-bed processes.

Synfuels China Engineering Company, Ltd. has leveraged the technology even further through enhanced integration with the world's best gasification technologies.

Under the leadership of Professor Yong Wang Li, Synfuels China has built up world-class R&D facilities thought China and beyond, adopting extensive chemical engineering research capabilities covering the full gamut of high throughput experimentation. The approach extends beyond deployment of commercial technology and delves into science and innovation, especially in catalyst development, in ways that are different from other Chinese companies.

Due to its breakthrough in indirect coal-to-liquids commercial technology, Synfuels China has won several awards, including the Outstanding Technological Achievement Award from Chinese Academy of Sciences, and the First Prize of National Energy Technological Advancement from National Energy Administration.

While this technology is commercial, one key to adaptation to the U.S. market is modularization. This can result in cost reductions and widespread use.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next stage?

\$20 million, for R&D, engineering, and reduced-scale prototype production, which has not been a focus to date as the current target markets (in China and other developing countries) have been addressing the challenge to scale up.

What is the magnitude and type of investment needed to take this technology commercial?

This technology is commercial. The next stage is modularization of the process, which would require approximately \$20 million.

What major hurdles or barriers to next steps of development need to be addressed?

R&D is required to adapt the process design to modularization, moving more of the construction of technology components from the field to the fabrication shop.

Synfuels Americas

Stepwise Liquefaction Technology

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MARKET SECTOR AND SIZE

- ☐ Carbon fibers ☐ Carbon resins ☐ Rare earth elements
☐ Sorbents ☐ Building materials ☐ Life science applications ☒ Transportation fuels
☒ Other: Chemicals

A novel stepwise liquefaction technology has been developed by Synfuels China to improve the efficiency of liquefaction for various feedstocks such as low-rank coal, heavy oil, coal tar, and biomass. Stepwise Liquefaction utilizes both Direct Coal Liquefaction (DCL) and Indirect Coal liquefaction (IDCL) technology.

Synfuels China has carried out comprehensive R&D work on DCL catalysis. Using a Chinese brown coal, the DCL process can convert 85-88% of the feedstock with an oil yield of up to 60%.

- The overall energy conversion efficiency could be increased from 44-47% to 50-55%
- The reaction conditions of the hydrogenation process are comparable with other processes.
- The oil product produced from stepwise liquefaction technology is easy to be refined and blended, and is suitable for the production of high-quality gasoline and diesel

In addition to brown coal, heavy oil and coal tar can also be used as feedstocks for Stepwise Liquefaction.

The scope of the market includes gasoline, diesel, jet fuel, kerosene, and chemicals. The products would be direct, coal-derived replacements for commodities currently produced from petroleum feedstocks.

Indicate the potential U.S. coal utilization from this technology, million tons/yr:

- ☐ <1 ☐ 1 to 10 ☐ 10 to 25 ☐ 25 to 50 ☐ 50 to 100 ☒ >100

LARGEST SCALE DEMONSTRATED

- ☐ None ☐ Laboratory or bench formulation ☒ Small pilot
☐ Large pilot ☐ First-of-a-kind demonstration at full scale ☐ Commercial

Tested with low rank coal

TIMING

Full commercial availability is feasible within:

☒ 1 year ☐ 3 years ☐ 5 years ☒ 10 years ☐ >10 years

TECHNOLOGY BENEFITS

NATIONAL SECURITY ☒ Reduction of import dependence ☐ Enhancement to international trade

☒ Provides redundancy of sourcing ☐ Other:

ECONOMIC ☒ Job creation ☒ Economic support to region in downturn

☒ Price advantage over alternative ☐ Other:

OTHER ☐ Environmental improvement ☒ Improved resource utilization

☐ Other: _____

This technology is being adapted for modularization, which would provide for production employment in a geographically diverse set of U.S. coal fields. Employment requirements per plant would be in the range of 50, not counting mining and support jobs. Commercialization would lead to the development and operation of numerous modular plants.

INVESTMENT AND BARRIERS

What is the magnitude and type of investment needed to take this technology to the next

The investment required would include additional laboratory-scale R&D for testing new concepts that are envisioned for the process, and additional pilot testing before moving to a large scale pilot. This cost is envisioned to be approximately \$20 million.

stage?

What is the magnitude and type of investment needed to take this technology commercial?

Getting through a large-scale (modular) pilot will require approximately \$150 million (total),

What major hurdles or barriers to next steps of development need to be addressed?

The major hurdles to the next step (large pilot) are:

- Modeling and laboratory process work to optimize the process for selected U.S. low rank coals.
- Development of a modular large scale pilot design
- Securing all of the required financing for a large scale pilot.

APPENDIX C

Acronyms

°C – Degree Centigrade	EERE – Energy Efficiency and Renewable Energy
°F – Degree Fahrenheit	EIA – Energy Information Administration
% – Percent	EOR – Enhance Oil Recovery
\$ – Dollar	EPA – Environmental Protection Agency
3D – Three dimensional	ERDA – Energy Research and Development Administration
ACCP – Advanced coal conversion process	ESA – Energy Security Act
Al – Aluminum	EV – Electric vehicle
AMCA – American Coal Ash Association	Fe – Iron
AMD – Acid mine drainage	FE – Office of Fossil Energy
AMO – Advanced Manufacturing Office	FEED – Front-end engineering and design
AVS – Antelope Valley Station	FOA – Funding opportunity announcement
BACT – Best available control technology	FOAK – First of a kind
bbl – barrel	FT – Fischer-Tropsch
BOF – Basic oxygen furnace	FY – Fiscal year
BOM – Bureau of Mines	GDP – Gross domestic product
BPD – Barrels per day	H – Hydrogen
BDY – Barrels per year	H ₂ – Hydrogen
BTU – British thermal unit	H ₂ S – Hydrogen disulfide
BTX – Benzene, toluene and xylene isomers	Hg – Mercury
C2P – Coal-to-products	HCCM – High-conductive carbon material
CAGR – Compound annual growth rate	HM/UHM – high modulus and ultra-high modulus
CAPEX – Capital expense	iCAM – Carbon Advanced Materials Center
CBTL – Coal/biomass to liquids	ICL – Indirect coal liquefaction
CCPI – Clean coal power initiative	IEA – International Energy Agency
CCPs – Coal combustion products	IGCC – Integrated gasification combined cycle
CCR – Coal combustion residuals	iPark – Industrial Innovation and Invention Park
CCT – Clean coal technology	ITC – International Trade Commission
CCUS – Carbon capture, utilization and storage	Kg – Kilogram
CDL – Coal-derived liquids	kWh – Kilowatt-hour
CM – Critical material	KY – Kentucky
CO – Carbon monoxide	LA – Louisiana
CO ₂ – Carbon dioxide	LCA – Life cycle analysis
COTC – Crude oil to chemicals	LD – Linz-Donawitz
CPCPC – Consortium for Premium Carbon Products from Coal	LFC – Liquids from coal
CTC – Coal-to-chemicals	LNG – Liquefied natural gas
CTL – Coal-to-liquids	LPG – Liquid propane gas
Dakota Gas – Dakota Gasification Company	LPMEOH – Liquid-phase methanol
DCL – Direct coal liquefaction	m – meter
DBP – Disinfectant byproduct	MATS – Mercury air toxics standards
DHS – Department of Homeland Security	MedTech – Medical technology
DME – Dimethyl ether	MD – Maryland
DOD – Department of Defense	mm – Millimeter
DOE – Department of Energy	MO – Missouri
DOI – Department of the Interior	MMBTU – Million metric British thermal units
DOL – Department of Labor	MMlb – Million pounds
DOT – Department of Transportation	MMst – Million short tons
DRB – Demonstrated reserve base	MTPY – Million tons per year
EAF – Electric arc furnace	MMTPY – Million metric tons per year
EAR – Export Administration Regulations	MRC – Micronized refined coal
ECA – Electrically calcined anthracite	
EDA – Economic Development Administration	

MRL – Manufacturing Readiness Level
 MS – Mississippi
 MTA – Methanol to aromatics
 MTG – Methanol-to-gasoline
 MTO – Methanol to olefins
 MTP – Methanol to propylene
 MTPD – Million tons per day
 MW – Megawatt
 N – Nitrogen
 NASA – National Aeronautics and Space Administration
 NCC – National Coal Council
 NEPA – National Environmental Policy Act
 NETL – National Energy Technology Laboratory
 NextGen – Next generation
 NGLs – Natural gas liquids
 NH₃ – Ammonia
 Ni – Nickel
 NIH – National Institute of Health
 NIST – National Institute of Science and Technology
 NO_x – Nitric oxides
 NPK – Nitrogen, phosphorous and potassium
 O – Oxygen
 OK – Oklahoma
 OSTP – Office of Science and Technology Policy
 PA – Pennsylvania
 PAHs – Polycyclic aromatic hydrocarbons
 PAN – Polyacrylonitrile
 PDF – Process-Derived Fuel
 PET – Polyethylene terephthalate
 ppm – parts per million
 PPT – Pounds per ton
 PRB – Powder River Basin
 prep – Preparation
 PSI – Physical Sciences, Inc.
 PVC – Polyvinyl chloride
 QIT – Quebec Iron and Titanium
 R&D – Research and development
 RCRA – Resource Conservation and Recovery Act
 REE – Rare earth elements
 REMS – Radically engineered modular systems
 REOs – Rare earth oxides
 ROM – Rough order of magnitude
 RF – Radio frequency
 ROI – Return on investment
 S – Sulfur
 SASOL – South African Synthetic Oil Liquids
 SCF – Standard cubic feet
 SFC – Synthetic Fuels Corporation
 SiC – Silicon carbon
 SNG – Synthetic natural gas
 SOTA – State-of-the-art
 SO_x – Sulfur oxides

stons – short tons
 Synfuels Plant – Great Plains Synfuels Plant
 Syngas – Synthetic gas
 Ti – Titanium
 TN – Tennessee
 TPD – Tons per day
 TPH – Tons per hour
 TRL – Technology Readiness Level
 TPY – Tons per year
 TX – Texas
 UHM – Ultra-high modulus
 UHP – Ultra-high power
 U.S. – United States
 USA – United States of America
 USD – United States dollar
 USDA – United States Department of Agriculture
 USGS – United States Geological Survey
 V – Vanadium
 VOCs – Volatile organic compounds
 VLCTL – Very large coal to liquid
 Vs. – Versus
 wt% – weight percent
 WV – West Virginia
 WVU – West Virginia University
 WY – Wyoming